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Planning Assistance To States Program

Massachusetts Wetlands Restoration Study: A REVIEW OF PROJECT MONITORING PROCEDURES

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US Army Corps
of Engineers
New England Division

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13. ABSTRACT (MAXIMUM 200 WORDS)

The purpose of this study was to assist the Wetlands Restoration and Banking Program (MWRP) in evaluating wetland restoration monitoring strategies for the Commonwealth. The report discusses the different project contexts within which monitoring is conducted; provides guidance for establishing performance criteria; recommends a monitoring framework based on a review of two approaches to monitoring; and discusses the use of reference wetlands for evaluating restoration project success. The study was conducted under the authority contained in the Section 22 Planning Assistance to States Program.

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Massachusetts Wetlands Restoration Study:
A Review of Project Monitoring Procedures

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1.0 Study Authority

Authority to conduct this study is contained in Section 22 of the Water Resources Development Act of 1974, Public Law 93-251, as amended. The Section 22 Planning Assistance to States Program authorizes the Corps to assist states in the preparation of plans for the development, utilization, and conservation of water resources.

This report is part of a four part effort conducted by the New England Division of the U.S. Army Corps of Engineers at the request of the Commonwealth of Massachusetts, Executive Office of Environmental Affairs (EOEA), Wetlands Restoration and Banking Program. Part one explored options for wetlands banking in Massachusetts. Part two consisted of the development of a method for identifying and evaluating potential wetland restoration sites. Part three consists of an evaluation of restoration project monitoring strategies for the Commonwealth. Part four is a case study in the Neponset River Watershed using the site identification and evaluation methodology developed in Part two.

2.0 Introduction

Monitoring is an important element of almost any wetland restoration plan. There are at least four reasons for monitoring: 1) to identify implementation problems and provide information to formulate mid-course corrections; 2) to confirm that restoration activities have taken place; 3) to measure success of the project; and 4) to provide information for implementing future restoration projects. The monitoring plan can provide the basis for setting project goals and reevaluating project progress through planning, design, implementation, and on into the life of the project.

The are seven characteristics of a good monitoring program. The monitoring program should: 1) begin in the early stages of project planning; 2) be appropriate to the scale of the restoration project; 3) require data of the highest quality practicable for the scale of the project; 4) be flexible to allow adjustments as information is collected; 5) specify time intervals between inspections; 6) document those responsible for monitoring; and 7) consider the relationship of the project to its watershed.

This report discusses the different project contexts within which monitoring is conducted; provides guidance for establishing performance criteria; recommends a monitoring framework based on a review of two approaches to monitoring; and discusses the use of reference wetlands for evaluating restoration project success.

3.0 Background

Successful wetland restoration occurs when the goals and objectives established for each project during planning are achieved (NRC, 1992). There are no universally accepted measures of success (NRC, 1992) and the development of "cookbook" criteria or detailed standards for monitoring different sites is impractical (Kusler and Kentula, 1990; NRC, 1992). Because of the fine tolerances of wetland characteristics and the large variety of wetland types and sites, specific monitoring criteria based on goals and objectives must be established for each project. Criteria such as the establishment of vegetation that covers a percentage of the site and exists for a defined period of time do not indicate that a project will function properly or persist over time (Kusler and Kentula, 1990). Therefore, this report suggests guidelines for establishing a project-specific monitoring program, rather than general criteria that indicate success.

4.0 Proactive vs. compensatory restoration monitoring

The rigor and comprehensiveness of monitoring programs should differ depending on whether the project is being conducted solely to improve the value of the resource - proactive restoration - or whether it will serve as compensation for unavoidable wetland impacts as a result of a permit action under a regulatory program.

Less rigorous monitoring should normally be required for proactive projects. Proactive restoration is intended to produce an overall net gain in functions and the individuals involved usually have long-term wetland protection and management goals (NRC, 1992). The ultimate measure of success for proactive restoration projects should be whether the wetland functions better than prior to restoration. Monitoring in this context should normally measure net gains and losses (tradeoffs) against baseline conditions and provide information to guide implementation, mid-course corrections, and future restoration efforts. As the National Research Council (1992) stated:

> "An attempt to achieve 100 percent success in a restoration is a desirable, but not essential, criterion for undertaking projects...The important decision is to begin the highly worthwhile process of restoring wetlands..."

and

> "...perfection should not be expected in restoration, and restoration planners must recognize that restoration is an exercise in approximating prior conditions."

In contrast, compensatory restoration projects are intended to compensate for lost functions resulting from a permitted activity. The monitoring program must be sufficiently rigorous and comprehensive to ensure that lost functions are replaced. For several reasons, the requirements for successful restoration are often unfulfilled for compensatory restoration: 1) mitigation projects are often poorly designed due to designers lack of interdisciplinary expertise (i.e., teams composed of biologists, hydrologists, engineers, soil scientists, etc.); 2) landowners often prepare the least expensive and least time consuming restoration plan acceptable and are rarely motivated to complete the restoration or make mid-course corrections; 3) compensatory wetlands restoration often involves small, widely separated wetlands, threatened by adjacent land uses; 4) wetlands restored for mitigation often receive little management after initial restoration (NRC, 1992). In addition, developers often do not allow the consultants that designed the mitigation project to supervise its construction. Incorporating an appropriate monitoring program into permit documents, including reporting requirements and regulatory agency inspections, alleviates some of these problems.

Some level of flexibility should also be maintained in compensatory project monitoring. Compensatory mitigation is considered only after opportunities for avoiding and minimizing impacts have been exhausted. When an unavoidable impact will occur, it is important to determine whether the former functions have been adequately replaced; compensatory restoration projects should result in no-net-loss of wetland functions. However, given the fact that compensatory mitigation often occurs off-site under conditions that differ from the impacted site, flexibility should be maintained to take advantage of the potential to maximize net benefits based on site-specific constraints. For instance, if monitoring shows that wildlife habitat is not meeting an objective due to unexpected site limitations, but fishery value is exceeding objectives, it should be permissible to make trade-offs on a case by case basis to maximize overall net benefits.

5.0 Guidance for Establishing Monitoring Criteria

The monitoring program should be developed while the project is being formulated and should be reconsidered as new information develops. The first step in establishing a monitoring program is to set project goals and objectives. Goals and objectives formulated during project planning are the basis for the establishment of monitoring criteria. Goals are the target functional attributes to be restored, such as water quality, hydrology, or wetland flora and fauna. Objectives are more precise, such as the specific characteristics of water quality to be achieved or the species composition of the various communities of biota to be restored. Specific, measurable performance indicators are specified for each objective. Performance indicators are specific, measurable quantities such as pH, percent vegetation cover, or Secchi disk visibility (NRC, 1992).

Restoration projects should be evaluated against a range of specific objectives to provide a measure of relative success based on a graded scale of achievement (NRC, 1992). The following guidelines for assessment criteria closely follow the recommendations of the National Research Council (1992) :

- o Criteria, linked to the objectives of the restoration project, should be established well before the assessment takes place.

- o Assessment criteria should include both structural and functional attributes of the ecosystem.

- o Overlapping criteria should be included to limit judgement errors.

- o Watershed based criteria should be used for off-site mitigation.

- o Direct measurement of wetland functions should be required wherever the scale of the project allows to establish a strong correlation between functions and indirect indices.

- o Assessment should take into account both temporal variation and spatial heterogeneity by requiring statistically adequate sampling and maintaining flexibility to accommodate differing rates of development.

- o There should be an *a priori* indication of how similar the restored system could ever be to the predisturbance or reference system(s) and a realization that reference sites as well as different parts of the same system will have a certain natural dissimilarity.

- o There should be an *a priori* time frame, based on the type of wetland and function, within which the system is expected to achieve the required similarity to predisturbance or reference systems.

- o Until critical time intervals for long-term assessments are developed, evaluations be should be conducted at 1, 2, 3, 5, and 10 years and also at 15 and 20 years for wooded swamps. Monitoring should be maintained long enough to determine whether sites can withstand unusual events, such as floods and droughts, but permittees should be released of monitoring responsibilities once conditions are assured of reaching a baseline.

6.0 Evaluation Methods

Comprehensive monitoring of restored wetlands is difficult because of the number of functions provided by wetlands and the large variability among wetland types and levels of function. Neither WET nor HEP, the two most well known assessment methods, was developed to compare the functioning of restored and natural wetlands (NRC, 1992). Two comprehensive methods are available and a third is under development by the Corps of Engineers. The two methods discussed in this report differ in their approach. The "Guide for Wetland Mitigation Project Monitoring" developed for the Washington State Department of Transportation emphasizes direct measurement of functions compared to literature-based criteria, whereas, "An Approach to Improving Decision Making in Wetland Restoration and Creation" developed by the U.S. Environmental Protection Agency, Environmental Research Laboratory emphasizes reference wetlands and indirect indices.

6.1 Guide for Wetland Mitigation Project Monitoring

The "Guide for Wetland Mitigation Project Monitoring" (the Guide) was developed for the Washington State Department of Transportation. It was authored by Richard R. Horner and Kenneth J. Raedeke of the University of Washington. Copies are available from the National Technical Information Service, Springfield, Virginia. The Guide consists of two parts. Part I describes the overall planning, design, implementation and interpretation of a mitigation monitoring program. It describes two types of monitoring based on purpose: 1) Assessing the Achievement of Functional Objectives, which involves documenting the development of wetland characteristics and functions and 2) Diagnostic Procedures that can aide in design or be used to analyze problems that develop in a mitigation project. Part II describes the individual tasks that may be implemented to collect information to monitor specific functions.

Success is evaluated based on the degree to which a mitigation project achieves the objectives established as part of the planning process, consistent with the recommendations of the National Research Council. Design of a monitoring program using the Guide involves identifying tasks that should be implemented to assess the achievement of project objectives. The Guide contains combinations of tasks that can be used to assess the capacity of a wetland to provide food chain support; ecosystem diversity; wildlife habitat; fish habitat; flood storage and desynchronization; water pollutant removal and retention; and shoreline anchoring. It does not provide specific procedures for monitoring groundwater recharge and discharge; however, information from some of the tasks that are described can be used to make subjective determinations about exchanges between surface and groundwater.

The monitoring tasks (shown in Table 1) are grouped under the following categories: 1) Mapping and Hydrologic Tasks, 2) Water Quality Tasks, 3) Soil and Sediment Tasks, 4) Primary Producer Monitoring Tasks, and 5) Consumer Monitoring Tasks. Each of the monitoring task descriptions includes, as appropriate, the background and purpose of the task; equipment and supplies needed to carry out the task; the procedures for the design of a sampling or observational program; a description of the process of sampling or observing; and methods for the analysis of samples, calculations, and interpretation of data to make an evaluation. A monitoring program is designed by selecting a set of tasks that will provide information to evaluate whether objectives have been achieved. Appropriate tasks are selected from a matrix of tasks and functional objectives.

The methods are somewhat rigorous; however, not every function must be monitored for every project. For instance, an extreme example would be a case where a flood control dam is constructed. In this case, it would not be necessary to monitor a compensatory mitigation site for its flood storage/ desynchronization value since this function would have been more than replaced at the original project site. The full program is unlikely to be required at any one site due to the unevenness of wetland functioning. A possible exception is a large mitigation bank where a high level of comprehensiveness and rigor would be appropriate. For small isolated mitigation projects (i.e., 5,000 sq. ft.), monitoring plans should emphasize the size and vegetation characteristics (percent cover, dominance type, and diversity) with additional emphasis placed on design standards to achieve success in replacing functions.

The review of the Guide by the New England Division concluded that it provides an excellent framework for developing guidelines for individual monitoring efforts. The use of rigorous, generally accepted, direct methods for collecting data and evaluating functional achievement makes this method a good approach to restoration site monitoring. It incorporates the goals and objectives established during planning, can be adjusted to the scale of the project, and supplies information for mid-course corrections. All of the methods described are transferable to Massachusetts because it emphasizes generally accepted sampling techniques. The largest problem with the Guide is that it does not include tasks for monitoring groundwater. In

Table 1. Monitoring Tasks from the Guide for Wetland Mitigation Project Monitoring

- Mapping and Hydrologic Tasks
  - Wetland Mapping
  - Transect Establishment
  - Photographic Record
  - Water Level Gaging
  - Crest Stage Gaging
- Water Quality Tasks
  - Water Temperature and pH Measurement
  - Dissolved Oxygen Measurement
  - Specific Conductivity Measurement
  - Determination of Pollutant Removal and Retention
- Soil and Sediment Tasks
  - Soil Organic Content Measurement
  - Soil Texture Analysis
  - Sediment Accumulation Gaging
  - Shoreline Stability Monitoring
  - Assessment of Hydric Soil Conditions
- Primary Producer Monitoring Tasks
  - Plant Community Assessment
  - Phytoplankton Biomass Measurement
  - Habitat Suitability Evaluation
- Consumer Monitoring Tasks
  - Aquatic Invertebrate Community Assessment
  - Fish Habitat Survey
  - Wildlife Population Characterization

the interim, two Corps of Engineers Technical Notes (Appendix A) provide information that can be used as guidance to establish appropriate monitoring tasks where groundwater relationships are a concern. If Massachusetts accepts the Guide as its framework for monitoring, groundwater monitoring tasks should be developed.

6.2 An Approach to Improving Decision Making in Wetland Restoration and Creation

"An Approach to Improving Decision Making in Wetland Restoration and Creation" (the Approach) (Kentula et al., 1992) is based on the use of natural wetlands as models to define standards for restoration and creation projects. The Approach involves comparisons of samples of populations of natural wetlands and completed restoration projects to create two groups of reference sites. (A discussion of regional reference sites is presented in the following section of this report.) The reference sites are selected within an ecoregion and grouped based on the surrounding land use and watershed position. Assessments of the functions and characteristics of these sample populations are compared to the results of restoration project monitoring programs using performance curves.

Performance curves are a tool to measure and display the development of wetland functions over time. They are developed with data generated by monitoring natural and restored reference sites. The following management questions can be answered using performance curves:

- What level of function is achievable for natural wetlands and projects in a particular land use setting?
- Do the projects achieve the same level of function as natural wetlands?
- How long does it take for projects to achieve the desired level of function?
- How can monitoring be timed so as to obtain the most reliable information?

An idealized hypothetical performance curve is shown in Figure 1. Points A-D are described in the text of the figure. It is important to note that, as shown by the standard error around line D in Figure 1, the condition and functions of natural wetlands varies over time. In addition, the shape of performance curves will vary with wetland type and the function displayed. Figure 2 shows some other possible shapes of performance curves.

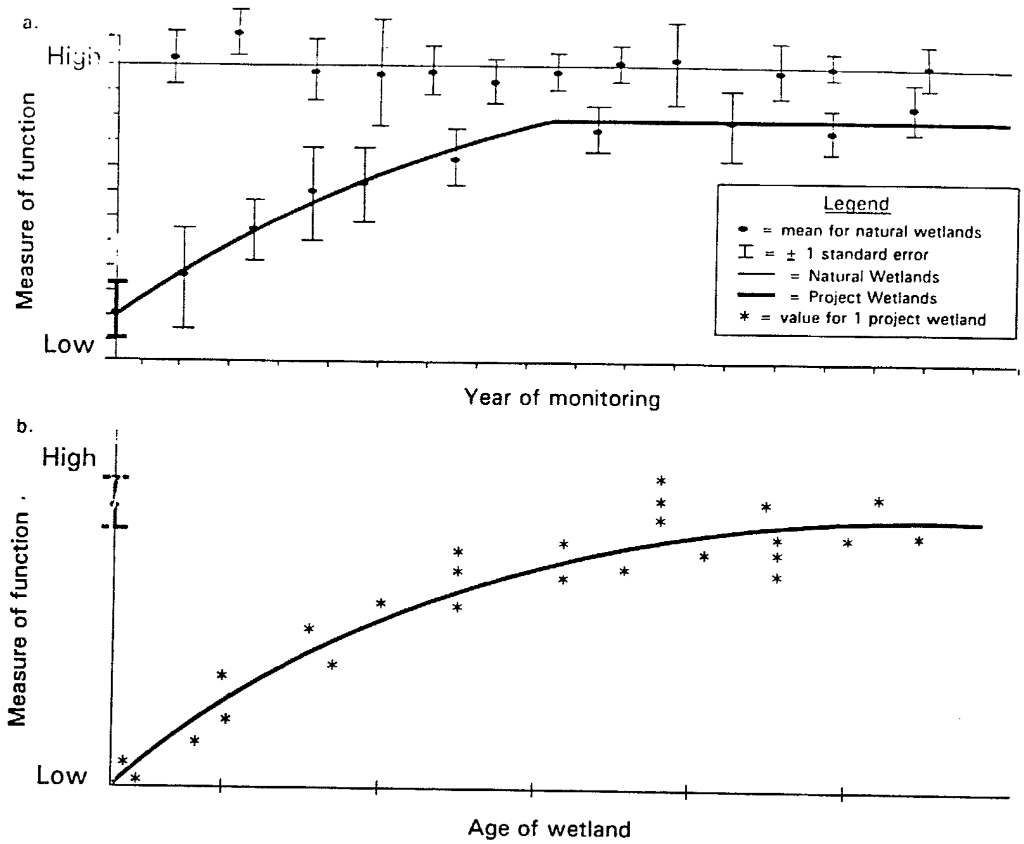
Monitoring procedures presented in the Approach are grouped into three levels: 1) documentation of as-built conditions; 2) routine assessments; and 3) comprehensive assessments. Table 2 lists the assessment variables, rationale for the variable, and suggested uses for all levels. Table 3 lists recommended methods for evaluating each of the variables. Appropriate variables are selected based on the assessment level, project goals and objectives, and the nature of the monitoring effort.

As-built conditions are assessed to document any variations from the authorized restoration plan and to serve as the baseline for further monitoring. These assessments immediately follow completion of a project.

Routine assessments consist of visual assessments of conditions which are compared to maps and photographs from prior site assessments. They are conducted during the first few years after a project is implemented and repeated at appropriate intervals. The information collected during routine assessments is used to: 1) identify problems that require correction; 2) provide a record of progress; and 3) determine when site performance warrants releasing the contractor from further responsibility, as appropriate. Results are summarized in a monitoring report.

Comprehensive assessments are conducted to: 1) identify modifications to the site that are required to meet project objectives; 2) provide a basis for evaluating project design and establish performance criteria; 3) help explain why a wetland project was or was not successful; and 4) support long term research efforts. Comprehensive assessments are performed after sufficient time has elapsed following implementation to allow major wetland characteristics to develop. These assessments include an evaluation of the performance of the wetland project over time.

Although the three level of assessment and performance curves may be useful, full implementation of the Approach in Massachusetts is not recommended because its reliance on reference wetlands and ecoregion evaluations would be cumbersome. Another concern with the Approach is its reliance on performance indicators, rather than direct measures of wetland functions. The authors favor the use of indicators because they feel that measures of wetland structure are readily available and more often meet the requirements of expediency and economy than do direct measures of function. However, indicators do not measure performance directly and therefore do not necessarily describe the actual level of functioning. Wherever possible, direct indicators should be favored over indirect indicators. Indirect indicators may be appropriate for monitoring small restoration projects, however.



Hypothetical performance curves. a) Example of hypothetical performance curve where the same samples of populations of projects and natural wetlands are followed Through time. b) Example of hypothetical performance curve where measurements are taken at one time from a sample of a population of projects of various ages and a sample of a population of natural wetlands.

Figure 1. Hypothetical performance curves.

Source: Kentula et al., 1992

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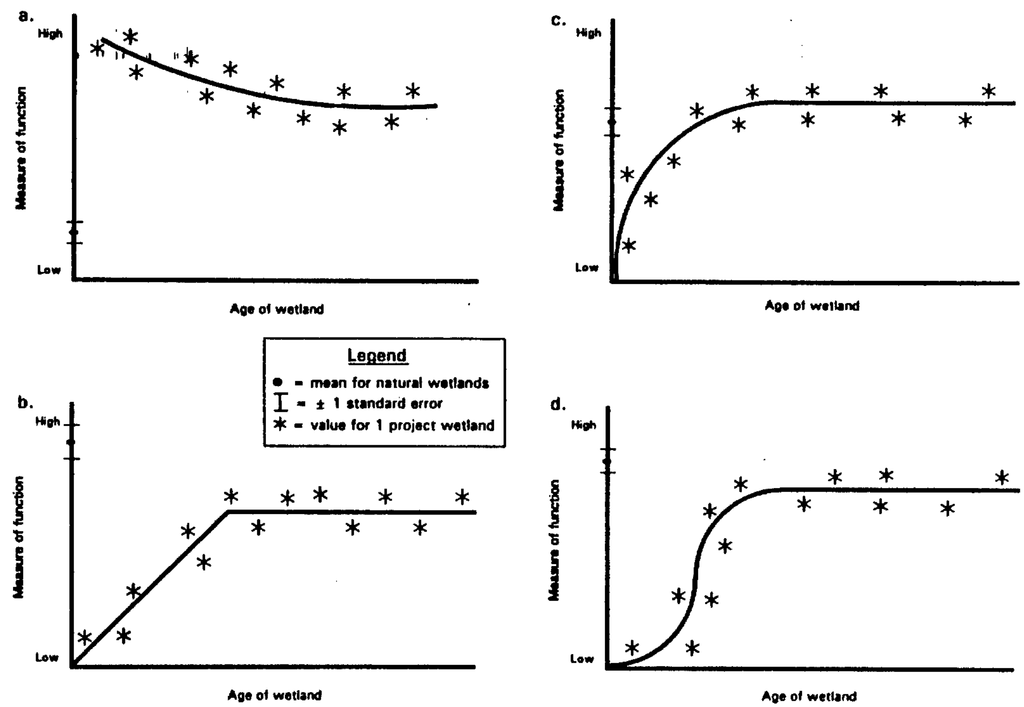

Examples of shapes a performance curve might take. a) Projects initially have a higher level of function than natural wetlands, but with time the level of function decreases and approaches the average for the natural wetlands; b) The level of function of the projects increases at a constant rate over time (linear relationship) and then levels off; c) The level of function of the projects increases quickly with time and then levels off (quadratic relationship); and d) The level of function of the projects increases slowly, then quickly, then levels off (logistic relationship).

Figure 2. Examples of performance curves.

Source: Kentula et al., 1992

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VARIABLE	RATIONALE/FUNCTION	SUGGESTED USE(S)
GENERAL		
Location (1)	identifies site on local map	provide baseline map for future assessments
Wetland type (1, 2, 3)	documents project goals (1), successional changes over time (2, 3)	serve as benchmark for future comparisons (1), document expected/appropriate development of the project (2, 3)
Drainage area (1)	determines position in watershed and related functions, flood storage computation	relate to projects functional capability
Surrounding land use (1, 2, 3)	determines inputs to wetland (e.g., nonpoint source pollution, industrial outfalls)	evaluate the need for buffers around wetland, explain changes in wetland performance
MORPHOMETRY		
Area (1, 3)	documents project goals (1), influences habitat value (3), and flood storage (3)	compare to project goals, construction specifications, and future assessments
Slope (1)	influences hydrologic gradient, plant establishment, animal access, characteristics of wetted edge	determine minimum, maximum and mean depths and slopes from topographic profiles for each transect (Figure 4-2)
Perimeter-to-area ratio (1, 3)	influences habitat, edge effect, project goals	determine variation in shape from original design (1), and changes in shape over time (3)
HYDROLOGY		
Water depth (1, 2, 3)	influences flood storage potential, vegetation patterns, wildlife and fisheries habitat	determine hydroperiod, flood storage (Simon et al. 1988), proportion of open water, temporal/seasonal changes
Flow rates (1, 3)	affects wetland characteristics and stability	evaluate water sources, hydrologic modeling
Flow patterns (1, 2, 3)	influences plant establishment and substrate stability and chemistry	serve as benchmark for future assessments of performance

Rationale and uses of variables measured in as-built (1), routine (2), and comprehensive (3) assessments of wetland projects and natural wetlands using "An Approach to Improving Decision Making in Wetland Restoration and Creation."

Source: Kentula et al., 1992

Table 2

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VARIABLE	RATIONALE/FUNCTION	SUGGESTED USE(S)
HYDROLOGY (continued)		
Indirect indicators (1, 2, 3)	provides evidence of hydrology in absence of water during sampling, boundary delineation	establish presence and periodicity of hydrology
SUBSTRATE		
Soil depth (1, 3)	influences suitability as planting and growth medium	verify construction specifications
Soil color (1, 3)	indicates hydric characteristics	determine extent (1) and time of formation of hydric soils (3), boundary delineation
Soil texture (1, 3)	influences suitability as planting and growth medium, root growth and infiltration	verify construction specifications, benchmark for temporal changes
Soil source (1)	provides baseline information	verify construction specifications and identify potential plant propagules
Organic matter (1, 3)	indicates suitability as planting and growth medium, condition of soil processes (Langis and Zedler 1991)	compare to natural wetlands, document temporal changes
Sediment flux (3)	indicates potential for sediment accretion removal, disturbance	measure rates of sediment accretion or erosion for comparisons to natural wetlands, document temporal changes, document/correct erosion
VEGETATION		
Species lists (1, 3)	defines wetland type, habitat, and plant diversity	verify permit or project planting conditions, delineation, calculate weighted averages and ratios (see Chapters 5 and 6)
Coverage (1, 2, 3)	influences use as habitat	verify project goals, benchmark for future assessments
Survivorship (1, 3)	indicates effectiveness of planting methods, influences project goals	evaluate planting success, suggest replanting strategies (3)
VARIABLE	RATIONALE/FUNCTION	SUGGESTED USE(S)
FAUNA		
Observations (1, 2, 3)	indicates use as habitat	evaluate use by common, rare, and exotic species over time
Habitat evaluations (3)	evaluates potential habitat	determine habitat potential over time
Species or community specific sampling (3)	evaluates targeted species or groups of concern	evaluate presence and abundance data over time
WATER QUALITY		
Water samples (1, 3)	indicates water treatment at the site or, disturbance in or around the site	provide baseline data for specific project goals (1), evaluate water treatment function, explain variations in vegetative performance, correlate with faunal use (3)
ADDITIONAL INFORMATION		
Photographic record (1, 2, 3)	provides permanent record for permit file on condition of wetland and surrounding land use	benchmark for temporal assessments, allows for office review of wetland and surrounding buffer
Descriptive narrative (1, 2, 3)	provides additional information and explanation	benchmark for future comparisons

Table 2 Continued

VARIABLE	AS-BUILT	ROUTINE	COMPREHENSIVE
GENERAL			
Location (1)	use existing map or create map with property boundaries, scale, north arrow, date, latitude and longitude, county and state (add addresses in urban areas and landmarks in rural areas)		
Wetland type (1, 2, 3)	classify intended type(s) (Cowardin et al. 1979)	classify intermediate type(s) (Cowardin et al. 1979)	classify resulting types(s) (Cowardin et al. 1979)
Drainage area (1)	planimeter area from topographic map (ha)		
Surrounding land use (1, 2, 3)	estimate % of surrounding land use, and photograph major types within a minimum of 300 m from the site (Anderson et al. 1976)	estimate % of surrounding land use, and photograph major types within a minimum of 300 m from the site (Anderson et al. 1976)	estimate % of surrounding land use, and photograph major types within a minimum of 300 m from the site (Anderson et al. 1976)
MORPHOMETRY			
Area (1, 3)	determine jurisdictional boundary and use basic survey techniques (Figure 4-1) to create a map of the project (ha)		determine jurisdictional boundary (Federal ICWD 1989) and use basic survey techniques (Figure 4-1) to create a map of the project (ha)
Slope (1)	measure elevation changes at intervals along transects (see Figure 4-2, Gwin and Kentula 1990)		

Table 3. Recommended methods for evaluating assessment variables using the Approach.

Source: Kentula et al., 1992.

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VARIABLE	AS-BUILT	ROUTINE	COMPREHENSIVE
MORPHOMETRY (continued)			
Perimeter-to-area ratio (1, 3)	planimeter boundary of wetland indicated on the project map and based on jurisdictional boundary (m/ha)		planimeter boundary of wetland indicated on the project map and based on jurisdictional boundary (m/ha)
HYDROLOGY			
Water depth (1, 2, 3)	measure inundation above ground (staff gauge), depth below ground (shallow well, 50-75 mm (2-3") dia. slotted PVC pipe)	measure inundation above ground (staff gauge), depth below ground (shallow well, 50-75 mm (2-3") dia. slotted PVC pipe)	measure inundation above ground (staff gauge), depth below ground (shallow well, 50-75 mm (2-3" dia. slotted PVC pipe)
Flow rates (1, 3)	measure inflow and outflow discharge if present (m^3/s) with flumes or weirs		measure inflow and outflow discharge if present (m^3/s) with flumes or weirs
Flow patterns (1, 2, 3)	use direct observation to indicate major pathways on map	use direct observation to indicate major pathways on map	use direct observation to indicate major pathways on map
Indirect indicators (1, 2, 3)	record observations of indicators (Federal ICWD 1989)	record observations of indicators (Federal ICWD 1989)	record observations of indicators (Federal ICWD 1989)
SUBSTRATE			
Soil depth (1, 3)	use soil auger or dig pit to depth of compacted soil or liner (Federal ICWD 1989)		use soil auger or dig pit to depth of compacted soil or liner (Federal ICWD 1989)
Soil color (1, 3)	use Munsell color chart to determine chroma and hue of matrix and mottles (Federal ICWD 1989)		use Munsell color chart to determine chroma and hue of matrix and mottles (Federal ICWD 1989)

Table 3 continued

VARIABLE	AS-BUILT	ROUTINE	COMPREHENSIVE
SUBSTRATE (continued)			
Soil texture (1, 3)	use soil texture triangle to classify soil based on feel (Horner and Raedeke 1989)		use soil texture triangle to classify soil based on feel (Horner and Raedeke 1989) or standard methods
Soil source (1)	document source location and addition of any soil amendments (e.g., fertilizer, organic matter, salvaged marsh surface)		
Organic matter (1, 3)	sample during as-built assessment if salvaged marsh surface or other organic materials are added		determine ash-free dry weight from samples (USDA 1984, Blume et al. 1990, NLASI 1983)
Sediment flux (3)	install clay pads at substrate surface as reference points (Cahoon and Turner 1989)		install clay pads at substrate surface as reference points (Cahoon and Turner 1989)
VEGETATION			
Species lists (1, 3)	identify species and wetland indicator and native/introduced status (Reed 1988), document planting locations and methods	identify species and wetland indicator and native/introduced status (Reed 1988)	identify species and wetland indicator and native/introduced status (Reed 1988)
Coverage (1, 2, 3)	estimate cover visually to nearest 10%, map plant communities	estimate cover visually to nearest 10%, map plant communities	estimate cover visually to nearest 10%, map plant communities, collect plot data along transects (Brower and Zar 1984, Leibowitz et al. 1991), collect data for productivity studies
Survivorship (1, 3)	visually determine % of plants alive		visually determine % of plants alive, tag individual shrubs and trees

Table 3 continued

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VARIABLE	AS-BUILT	ROUTINE	COMPREHENSIVE
FAUNA			
Observations (1, 2, 3)	record direct and indirect observations of wildlife, fish and invertebrates	record direct and indirect observations of wildlife, fish and invertebrates	record direct and indirect observations of wildlife, fish and invertebrates
Habitat evaluations (3)	use Habitat Evaluation Procedures (FWS 1980) or comparable method for selected species		use Habitat Evaluation Procedures (FWS 1980) or comparable method for selected species
Species or community specific sampling (3)			select appropriate census techniques (Brooks and Hughes 1988, Brooks et al. 1991, Erwin 1988)
WATER QUALITY			
Water samples (1, 3)	measure appropriate parameters based on project objectives (e.g., pH, conductivity, total suspended solids, nutrients, pollutants)		measure appropriate parameters based on project objectives (e.g., pH, conductivity, total suspended solids, nutrients, pollutants)
ADDITIONAL INFORMATION			
Photographic record (1, 2, 3)	photograph wetland and surrounding landscape from several directions with 50mm lens using 35mm film from permanent photo stations (Horner and Raedeke 1989)	photograph wetland and surrounding landscape from several directions with 50mm lens using 35mm film from permanent photo stations (Horner and Raedeke 1989)	photograph wetland and surrounding landscape from several directions with 50mm lens using 35mm film from permanent photo stations (Horner and Raedeke 1989)
Descriptive narrative (1, 2, 3)	describe and explain notable features and changes for each major variable	describe and explain notable features and changes for each major variable	describe and explain notable features and changes for each major variable

Table 3 continued

Performance curves could be useful in setting realistic project objectives and performance criteria where sufficient data from direct measures of wetland characteristics and functions exists. Performance curves should be developed for as many wetland types and settings as possible when data becomes available from projects monitored using the guide. For instance, the performance of riparian red maple swamps with mineral soils will differ from that of depressional red maple swamps with organic soils. Wherever data exists, or as data is generated through monitoring of restoration projects or other scientific studies, it can be used to develop performance curves. The collection of data to establish these curves requires a long-term commitment to managing data from various sources as it becomes available. (See discussion of benchmark wetlands.) The MWRBP or another appropriate state agency should consider developing and updating performance curves for the various wetland types and settings in the Commonwealth.

6.3 Sampling Strategy and Data Requirements.

There are important considerations common to the design of any sampling strategy to ensure the quality of data. In most cases, regulatory agencies should require the use of compatible field techniques and analyses that will facilitate the comparison of results taken at different times at a project site or among projects monitored. For instance, water quality sampling methods should match those used by the Massachusetts Office of Watershed Management wherever possible. (See Table 4.) However, the methods described in the Guide and the Approach are not the only methods that should be accepted for monitoring programs. Regulators should maintain the flexibility to discuss other potential monitoring techniques which may be more appropriate under differing project circumstances. Improved methods should be incorporated into the program as they are developed.

Two general considerations on data quality are to take sufficient samples to obtain statistically significant results wherever practical and use generally accepted methods of sample collection and analysis. Kentula et al., (1992) provided a good summary of the considerations for collecting quality data. Some references for assessment techniques for various variables are provided in Appendix B.

7.0 Using Reference Wetlands to Evaluate Success

Using data from long-term reference wetland monitoring data sets is one of the options for evaluating wetland restoration project success. "An Approach to Improving Decision Making in Wetland Restoration and Creation" (the Approach) (Kentula et al., 1992) relies heavily on reference wetlands and the National Research Council (1992) recognized the need for appropriate comparison data sets for wetland monitoring. Horner and Raedeke (1989) cautioned that reference wetlands should be used as the principal basis for criteria only when a good match between reference and mitigation sites exists in most important respects.

The Washington State Guide to Wetland Mitigation Project Monitoring described three types of criteria to determine whether project objectives are achieved: 1) comparisons of monitoring results with values reported in the literature, 2) comparisons of monitoring results from mitigation and reference sites, and 3) comparisons of monitoring results from the mitigation site and the wetland that it is intended to replace. They compared the positives and negatives of each of these options and recommended a combination of the three be used with emphasis on literature based criteria. Massachusetts should use a combination of these three types of criteria and should develop a system to catalog the results of all restoration/mitigation projects to supplement information in the literature.

The baseline conditions of the wetland that will be impacted or restored should be the basis for establishing project goals and criteria and measuring results. In the case of mitigation projects, an evaluation of baseline conditions should be conducted to determine the existing functions and characteristics to set goals based on the significance and level of functioning. This information will form the basis for crediting on a functional basis. Since some functions and wetland characteristics take time to develop baseline information can be used to establish credit ratios for one:one functional replacement. In the case of proactive restoration projects, the baseline information is the basis for designing and evaluating functional improvement.

There are two types of reference wetlands: 1) natural wetlands, which will be referred to as natural reference wetlands and 2) restored or created wetlands, which will be referred to as restored reference wetlands.

Procedures in the Approach (Kentula et al., 1992), can be used to identify appropriate reference sites. Using this approach, the area at risk of wetland impacts is identified, then a list of all restoration and creation projects in the area is generated. Populations of projects (i.e., similar wetland types) are identified among the projects on the list. Then boundaries are established based on ecoregions to create homogenous subsets of projects within the population. In Massachusetts, most areas at risk will be smaller than the ecoregions within which they occur. Natural reference wetlands are selected to compare to the results of the restoration projects. Restoration projects and natural reference wetlands are stratified by land use setting so that the

Table 4. Analytical Methods Used by the Massachusetts Office of Watershed Management

Parameter	Method
BOD	EPA 405.1
Dissolved Oxygen	EPA 360.2
pH	EPA 150.1
Turbidity	EPA 180.1
Total Alkalinity	EPA 310.1
Suspended Solids	EPA 160.1
Total Solids	EPA 160.3
Settleable Solids	EPA 160.5
Total Kjeldahl Nitrogen	EPA 351.1
Ammonia-Nitrogen	EPA 350.1
Nitrate-Nitrogen	EPA 353.1
Total Phosphate	EPA 365.4
Total Coliform	Membrane filter technique
Fecal Coliform	Membrane filter technique
COD	EPA 410.1
Conductivity	EPA 120.1
Color	EPA 110.2
Chloride	EPA 325.3
Cadmium, copper, chromium, iron, lead, magnesium, manganese, nickel, zinc, hardness	EPA 200 series
Aluminum, tin	EPA 200.7A (ICP)
Hexavalent chromium	EPA 719.6, SWA 846

natural wetlands represent the various land uses surrounding the wetland projects. Sites to be sampled are randomly selected among the various subpopulations (i.e., stratified random sampling) (Kentula et al., 1992). These sites are monitored and performance curves are developed to evaluate success.

It would be an expensive and time consuming task to conduct these studies throughout the Commonwealth. Since monitoring will in all likelihood be required for future restoration and creation efforts, it would be more economically achievable to set up a database to record information from these efforts as it is developed. A database could be maintained by the MWRBP and made available to agencies and consultants for use in evaluating success. The Approach contains information on establishing such a database.

8.0 Establishing Long-Term Reference Wetlands

8.1 Background

A long-term database of information on wetland functions could be enhanced by establishing long-term reference wetlands or "benchmark wetlands" throughout the state. Long-term reference wetlands would consist of sites distributed throughout the Commonwealth that are repeatedly monitored to maintain an information base to which the results of individual monitoring efforts could be compared. The main purpose of long-term monitoring would be to provide reference sites to compare restored wetlands to natural wetlands.

A study is presently being conducted by the Environmental Research Laboratory of the U.S. Environmental Protection Agency to develop a set of reference data for a study area in the state of Oregon (Magee et al., 1993). The plan for the study, the "Research Plan and Methods Manual for the Oregon Wetlands Study," is designed to provide detailed characterizations of approximately one-hundred-fifty natural, created and restored freshwater wetlands. The results of the study are expected to be applicable to wetlands in other regions and the plan itself can be adapted for similar studies in other parts of the United States. The results are expected to be reported in the winter of 1995. In addition to adding to basic wetland knowledge, the study is intended to provide information to improve wetland management strategies and wetland project design.

Researchers implementing the OWS will collect data that can be used to characterize and compare the structural and functional attributes of populations of natural wetlands in different land use settings and populations of natural wetlands and wetland restoration and creation projects. The information generated in this study is intended to be used to aid in the development of performance criteria and design guidelines for restoration and creation projects and evaluate the results of management strategies and suggest alternatives. To a large extent, this methodology relies on various indicators of wetland functions rather than direct measurement of functions to enable researchers to evaluate a larger number of sites.

The researchers conducting the OWS feel that monitoring of a large number of sites will provide a better information base for addressing study objectives than would more detailed study of a small number of wetlands. They indicated that extrapolating the results from one site to other systems is unwise in most cases and data from a single site cannot provide insight into variability among wetlands of a given type or in a particular landscape setting.

An ecoregion approach, such as that used in the Approach, has been proposed as one possibility for selecting benchmark wetlands in Massachusetts. Ecoregions are areas (regions) of relative homogeneity in ecological systems (Galant et al., 1989). The selection of regional reference sites requires considerable time and analysis. The "The Massachusetts Ecological Regions Project" (MERP) report (Griffith et al., 1994) provided a process for reference site selection for surface water quality monitoring (Pages 15-16, Section 2 Stream Reference Site Selection). Again, the authors suggested a large number of candidate reference sites for each region to define different types of streams, encompass natural variability, and separate the less disturbed from more disturbed sites. The report concluded that the ecoregion/subregion framework is useful for environmental resource assessment and management. However, they indicated that modifications of the framework could be required in the future and significant time and effort will be required to fully understand attainable water quality conditions.

Nevertheless, long term, detailed studies of wetland functions are required to definitively document wetland functions given the temporal variability in wetland functioning. A few well selected long-term reference wetlands could provide important data for evaluating project success to augment the literature and results of restoration project monitoring required by regulatory agencies. The question is: How many sites should be established, of what wetland class and type, and where should they be located?

8.2 Identifying Reference Wetlands in Massachusetts

Regionalization of long-term wetland monitoring sites in Massachusetts is useful only if it improves the ability of managers to provide information for monitoring restored sites. Long-term reference wetlands should be selected to meet the following criteria:

- Reference wetlands should provide a comparative information base on natural wetlands to evaluate the success of restoration projects.

- Since success is based on restoring the fish and wildlife, water quantity, and water quality functions, regionalization will be useful only if some or all of these functions vary more significantly due to regional location than other factors, such as site type.

- The wetland types should be those most likely to be used for compensatory restoration.

Massachusetts has been divided into two ecoregions and thirteen subregions according to the MERP as shown on Figure 3. The Massachusetts Wetlands Protection Act recognizes five classes of wetlands to which one additional group "fens" could be added. A representative group of benchmark wetlands in Massachusetts, therefore, would include salt marshes, bogs, fens, swamps, freshwater marshes, and wet meadows. To have a representative of each wetland class in each ecoregion or subregion, as defined for the ecoregions project, would require eleven to sixty-nine (salt marshes occur in only one region and four subregions) benchmark wetlands. This number excludes the multiples that could be required to incorporate differences in vegetation and soil type, hydrologic regime, size, and geomorphic setting. Consideration of some or all of these characteristics would require an unrealistic number of benchmark wetlands. This large number of potential sites suggests that some consolidation or prioritization of sites is necessary.

The major regions for salt marshes in New England could be divided at Cape Cod. Tide range varies substantially north and south of Cape Cod (Teal, 1986) and it is a dividing line for some of the species of wildlife that inhabit salt marshes (e.g., seaside sparrow, clapper rail, and sharp-tailed sparrow-limit of year round resident range). However, in terms of restoration monitoring, there is probably at least as much variation among functions and characteristics of salt marsh geomorphic site types (i.e., back barrier, fluvial, bluff-toe, or transitional; Wood et al.,

1989) as regional location. In addition, the Wetlands Protection Act regulations essentially prohibit destruction of salt marsh, which means that the area of salt marsh impacts would be relatively low suggesting that they should have a low priority for the establishment of benchmark wetlands.

Bogs and fens, although they show significant variation within Massachusetts ecoregions from Atlantic white cedar dominated wetlands along the southern coast to the black spruce wetlands of the Berkshires, are very sensitive wetland types that are difficult to restore. Emphasis should be placed on protection of existing bogs and fens rather than restoration; therefore, benchmark sites for these types should be a lower priority for a restoration program.

The most common and most commonly impacted wetland type in Massachusetts is red maple swamp. Golet et al. (1993) indicated that red maple swamps comprise as much as 64% of the total wetland area in Massachusetts. Red maple swamps vary regionally in Massachusetts. Golet et al. (1993) indicated that the size, abundance, typical landscape position, edaphic characteristics, flora, and fauna of red maple swamps vary as a result of the physiographic and climatic diversity within the glaciated northeast. They indicated that, in terms of floristic composition, Massachusetts lies within two zones: The Southern New England Upland, Seaboard Lowland, and Coastal Plain; and the Northeastern Mountains) (Figure 4). However, the vast majority of the state lies within the Southern New England Upland, Seaboard Lowland, and Coastal Plain. Differences among red maple swamps in Massachusetts are more dependent on hydrogeomorphic type and other site-specific factors than ecoregion. In addition, unless a site already has mature trees, the results of monitoring red maple swamps would always differ from wetlands created to replace them due to the time required for trees to mature. It would therefore be more appropriate to monitor the successional precursors to red maple swamps and document functional development over time.

The successional precursors to red maple swamps are also the most likely wetlands to be restored or created because they are easier to restore. Kusler and Kentula (1990) indicated that a relatively high degree of success has been achieved with freshwater marsh restoration. Marshes and wet meadows, or emergent wetlands, and shrub swamps are the precursors of red maple swamps. Figure 5 from Golet et al. (1993) shows the major changes in a southern New England freshwater wetland over a 20- to 33-year period. Because these types, in particular emergent wetlands, are usually geologically younger than other wetland types, there are probably more similarities among emergent wetlands in different locations. Based on these considerations, the most useful long-term reference wetlands would be emergent and shrub swamps that show signs

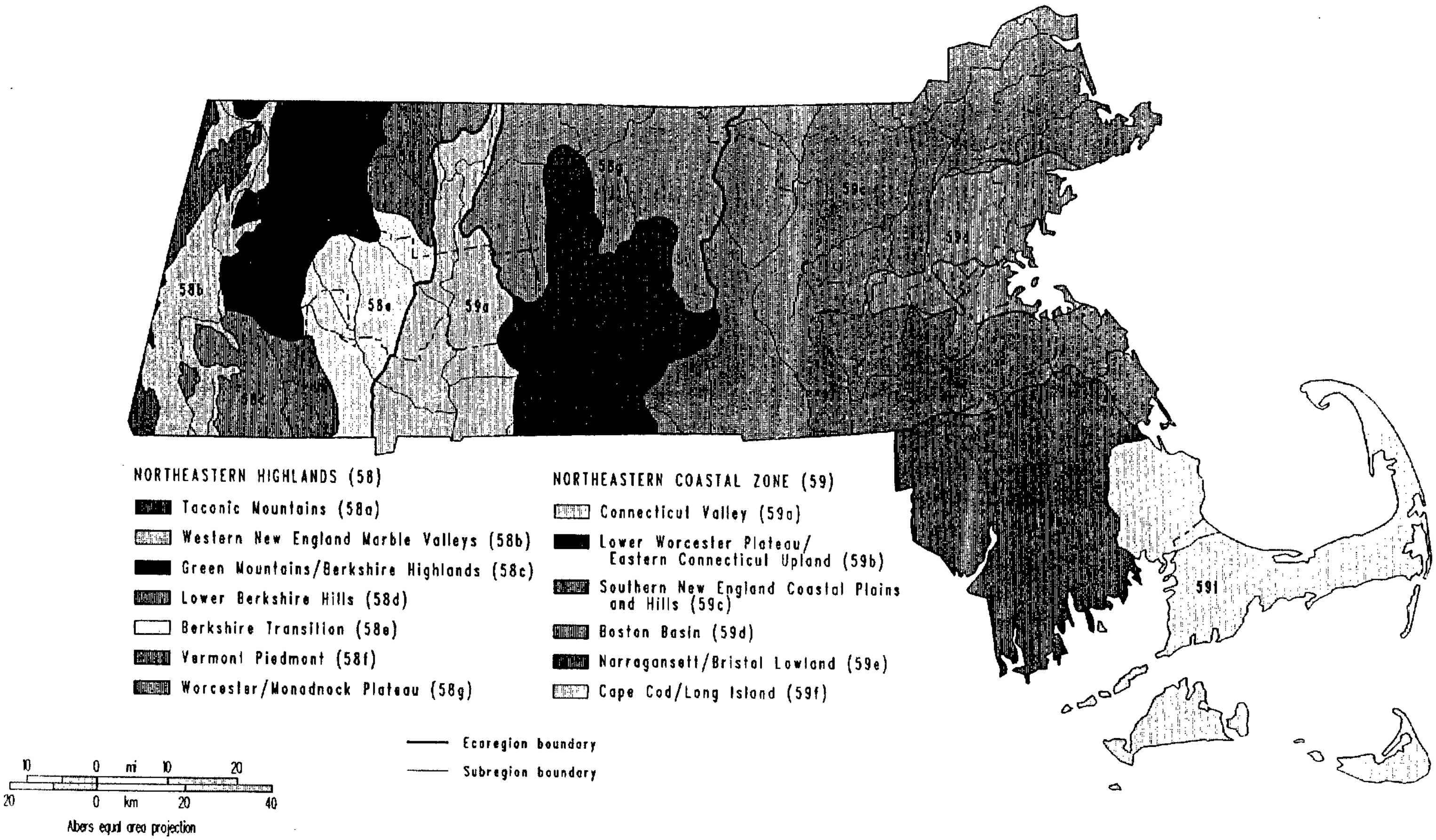

Figure 3. Ecoregions and subregions of Massachusetts.

Source: Griffith et al. 1994

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New England Division

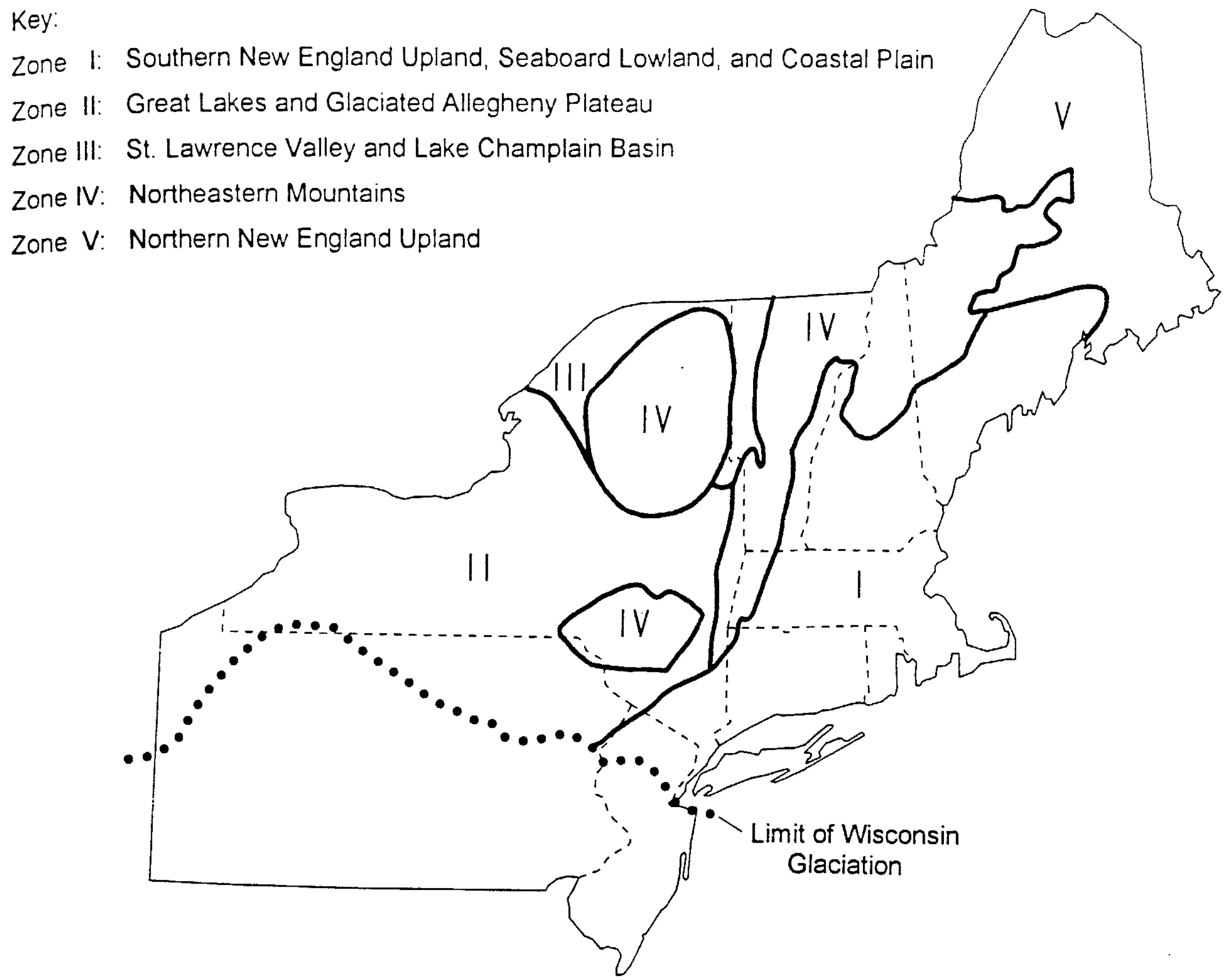

Figure 4. Zones of variation in floristic composition and relative abundance of red maple swamps in the glaciated Northeast.

Source: Golet et al. 1993

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US Army Corps of Engineers

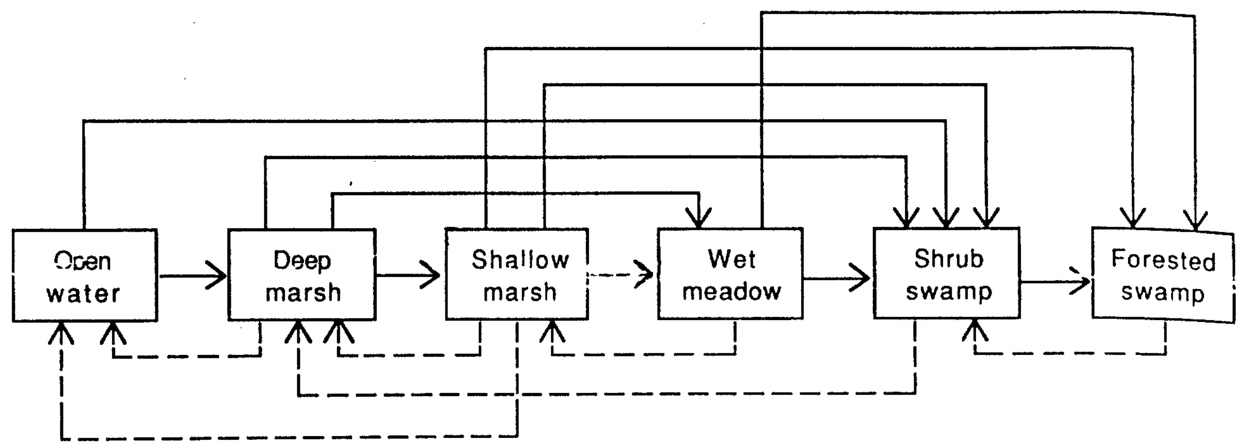

Figure 5. Major changes in southern New England freshwater wetlands over a 20- to 33-year period (based on Larson and Golet 1982 and Organ 1983). Progressive changes are indicated by solid lines, retrogressive changes by dashed lines (classification according to Golet and Larson 1974).

Source: Golet et al. 1993

US Army Corps of Engineers
New England Division

of succeeding toward red maple swamp. Establishment of benchmark wetlands in the vicinity of academic institutions in the Commonwealth (the Amherst area, central Massachusetts, eastern Massachusetts, and Cape Cod) would include any variations that do result from ecoregion position.

Perhaps the greatest value of long-term monitoring is that it improves our capacity to develop realistic expectations for restoration projects and increases the potential to represent the broad range in wetland characteristics to which restoration projects should be compared. Wetland characteristics, functions and values differ based on geographic location, wetland type, and the physical and biological characteristics of each individual wetland. The goal of reference sites should be to represent the broadest range of characteristics possible so that individual mitigation project monitoring results can be compared to the range with particular emphasis on that data available for the wetland types most characteristic of the impacted wetland.

9.0 Evaluating Success in Achieving Watershed Goals

The ultimate goal of watershed-based wetland management and restoration is to improve the overall environmental quality of the entire watershed; however, wetland restoration is just one tool affecting overall watershed functioning. Leibowitz et al. (1992) indicated that our understanding of how conversion and degradation affect wetland functions (in particular flood storage, water quality and habitat functions) at the landscape level is limited because few studies have examined degradation of wetland function on a large scale. To measure the success of watershed-based wetland restoration on watershed function would, at the least, require that the entire watershed restoration program be implemented. Modeling could be performed to assess the effect of the program the functions, such as flood storage, water quality enhancement, or fishery habitat, but this would be very expensive.

Many of the incremental changes achieved through wetland restoration will not be measurable at the watershed or basin scale. For instance, given the many ongoing programs to improve the quality of surface waters and their natural variability, it will be difficult to attribute an increase in water quality in a watershed to restoration of wetlands. The situation is similar for flood water storage and fish and wildlife functions. Assessment of the degree of achievement of these functions at the watershed scale will, for the most part, depend on how well the goals and objectives established during planning considered watershed needs. If the goals and objectives were targeted at watershed functional deficits and the performance criteria were met, the project can be assumed to have improved watershed functioning.

10.0 Conclusions

This report describes the different contexts for monitoring; provides guidance for establishing performance criteria for projects; recommends a monitoring framework based on a review of two different monitoring strategies; and discusses the use of reference wetlands for evaluating success. Specific monitoring methods are not provided. Rather, general guidance and an approach to monitoring are outlined for Massachusetts.

There are essentially two different contexts within which restoration projects and, therefore, monitoring are performed. Proactive restoration is conducted solely to improve the value of the resource. Compensatory restoration serves as compensation for unavoidable wetland impacts as a result of a permit action under a regulatory program. The monitoring guidance in this report can be applied to both types of projects, but it is important to distinguish between the two in establishing monitoring requirements. Monitoring requirements for compensatory restoration must be more stringent because in this context replacement of the loss incurred as a result of a permitted activity must be documented. There is no such compensation requirement associated with proactive restoration. The increase in functioning as a result of a proactive restoration project results in a net gain. Monitoring for proactive projects should be conducted to guide implementation and should not be so rigorous that it discourages projects.

There are several main themes that should guide restoration project monitoring in Massachusetts. First, general performance criteria, such as establishment of seventy percent cover of wetland vegetation, are not recommended except for the smallest compensatory restoration projects. It is clear that, due to the variability among wetland characteristics and wetland site types, development of generalized criteria is impractical. Instead, monitoring criteria should be linked to the goals and objectives established early in the planning of each project. Overlapping criteria that consider both structural and functional attributes of the wetland should be included.

In most cases, baseline conditions should serve as the benchmark against which success is measured. For proactive projects, the pre-restoration functions and conditions at the restoration site should serve as the baseline. For compensatory projects, the pre-impact functions and conditions at the site that will be impacted serve as the baseline. In this case, the baseline conditions at the restoration site must also be established to determine how the site should be restored (i.e., which characteristics should be manipulated to obtain the appropriate functions), to determine the functional capacity of the site and restoration area requirements, and to document the increase in functions achieved vs. the loss at the impact site. When available, the Hydrogeomorphic Method (HGM) for wetland evaluation can be used to guide this process.

Wherever practical, monitoring plans should require direct measurement of wetland functions. Wetlands are protected because of the important functions they provide, but the level of functioning of various wetland types has not been clearly established. By requiring direct measurement of functions, the actual net increase in the function of concern is documented and the state of knowledge about wetland functions is increased. Information about wetland functioning gained through monitoring can be applied to future projects and decisions.

When on-site, in-kind mitigation is exhausted as an option for compensatory restoration projects, watershed based criteria should be established.

Monitoring plans must include appropriate time frames, but be flexible enough to accommodate site-specific variation in the development of characteristics and functions. Plans should recognize that restored wetlands may not achieve the level of functioning of natural reference wetlands. Time frames for the development of wetland characteristics and functions should be established based on the wetland type and function of concern. For instance, the flood storage, sediment retention, and sediment stabilization functions should be nearly fully developed one full growing season after the completion of construction. Nutrient transformation and toxicant retention may require intermediate time periods to fully develop. Development of the wildlife habitat function will depend on the type of wetland restored: the wildlife value of marshes and wet meadows may be fully restored in one to ten years, while forested swamps may require twenty or more years to develop. Until critical time intervals for monitoring are developed, monitoring evaluations for large scale compensatory restoration projects should be conducted at 1, 2, 3, 5, and 10 years up to 15 and 20 years for forested swamps.

Two different monitoring methods were reviewed and are summarized in this report. They differ in approach. The "Guide for Wetland Mitigation Project Monitoring" (the Guide) developed for the Washington State Department of Transportation emphasizes direct measurement of functions compared to literature-based criteria, whereas, "An Approach to Improving Decision Making in Wetland Restoration and Creation" (the Approach) developed by the U.S. Environmental Protection Agency, Environmental Research Laboratory emphasizes reference wetlands and indirect indices. The Guide should be used to guide development of a monitoring program for Massachusetts because of its primary reliance on direct measures of wetland characteristics and functions and comparisons to literature based criteria, baseline conditions, and reference wetlands to measure success. The Guide does not define procedures for monitoring groundwater recharge, discharge, or other relationships of restored wetlands to groundwater. Massachusetts should develop procedures for groundwater monitoring to consider the relationship of groundwater to the overall water budget, temporal aspects of recharge and discharge, and annual water table fluctuations. Two Corps of Engineers Technical Notes (Appendix A) provide guidance that can be used to establish monitoring tasks for groundwater.

Performance curves are a tool, described in the Approach for measuring and displaying the development of wetland functions over time. Massachusetts should consider creating a database to record the information generated through monitoring efforts to be used to develop performance curves. This information could guide future monitoring and restoration efforts.

The report also considers the value of establishing long-term reference or "benchmark" wetlands to generate a database of information on wetland functions. Covering all wetland classes and site types in Massachusetts with benchmark wetlands would require a very large number of sites, so prioritization is recommended. An ecoregion approach to establishing benchmark wetlands was considered, but is not recommended since wetland functions differ more due to wetland class and characteristics than ecoregion in Massachusetts. The report recommends that successional precursors to red maple swamps be established as benchmark wetlands. Red maple swamps are the most abundant wetland type and most commonly impacted wetland type in Massachusetts. They are also difficult to replace in-kind due to the long period required for trees to mature, so it is important to generate information that can be used to determine if restoration sites are progressing toward success. This would allow the time frame for monitoring forested swamps to be shortened.

Finally, the report considers the evaluation of success in achieving watershed goals. Improvement in functions due to wetland restoration would be extremely difficult to measure at the watershed scale. Watershed goals can be considered to be met when the goals of individual projects established through watershed-based site selection are achieved.

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APPENDIX A
Groundwater Monitoring Technical Notes

Wetland Groundwater Processes

PURPOSE: This technical note summarizes hydrologic and hydraulic (H&H) processes and the related terminology that will likely be encountered during an evaluation of the effect of ground-water processes on wetland function. This technical note provides general guidance to personnel in the field who lack specific expertise in H&H processes but are still faced with the regulatory responsibility of wetland permit evaluation. Future technical notes will complement this overview by presenting more detailed information on data sources and methods of analyses associated with individual H&H processes.

BACKGROUND: The hydrologic and hydraulic characteristics of a wetland influence all wetland functions, and consequently should be an initial focus of an evaluation. The processes by which water is introduced, temporarily stored, and removed from a wetland are commonly known as the water budget. Water is introduced to a wetland through direct precipitation, overland flow (or runoff), channel and overbank flow, groundwater discharge, and tidal flow. Temporary storage includes channel, overbank, basin, and groundwater storage. Water is removed from the wetland through evaporation, plant transpiration, channel, overland and tidal flow, and groundwater recharge.

The relative importance of groundwater processes on the water budget varies with the wetland type (i.e., riverine, tidal, depressional), and regional factors such as climate, hydrogeology, and physiography. Useful reviews of the influence of groundwater processes in wetlands can be found in Carter and Novitzki (1986) and Winter (1988). To evaluate whether groundwater at a site influences wetland functions, it is important to understand individual groundwater processes, the role they can play in various wetland types, and how to evaluate their contributions to the water budget.

FACTORS AFFECTING GROUNDWATER FLOW: Groundwater flow is influenced by a number of factors, including hydraulic gradients, hydraulic conductivity, porosity, and storage coefficients. While these parameters are simple to understand, they are often difficult to quantify. Information on local and regional soil parameters and piezometric heads can usually be obtained through state and Federal Geological Surveys or the Soil Conservation Service (SCS). Data sources include databases such as the U.S. Geological Survey WATSTORE, state wetland inventories, soil surveys, and SCS soil maps.

- Hydraulic Gradients. The hydraulic gradient is the difference in piezometric head between two locations divided by the distance between them. Generally, this is measured by installing several wells, bore holes, or piezometers, and measuring the head in each. For groundwater flows to or from the surface water, the elevation of the surface water is the upper piezometric head.

- Hydraulic Conductivity. This is the ability of the soil to conduct water under hydraulic gradients. The hydraulic conductivity or permeability depends on soil characteristics such as type (i.e. clay or sand), size, shape, and packing. Hydraulic conductivity can be estimated in a number of ways (Driscoll 1986, Lamb and Whitman 1969). It can be roughly estimated, given the soil composition and texture, or calculated based on a soil size analysis. Local values of hydraulic conductivity can be measured by performing a slug test in a piezometer or well location. Field-wide measurements can be determined from an aquifer performance (pump) test, in which one well is pumped and the variation of the piezometric head in nearby wells is observed over time. Values of hydraulic conductivity have been found to range from 10^{-8} meter per second in clay soils to 10^{-2} meter per second in well-sorted gravel formations (SCS 1992).

- Porosity. Porosity is the fraction of a soil volume occupied by voids, and represents the potential area through which water can flow. It is usually measured in the laboratory from a soil sample, although knowledge of the soil type can give a fair estimate of porosity. Together with the flow rate calculated from Darcy's Law (Freeze and Cherry 1979), the soil porosity can be used to estimate groundwater travel times.

- Storage Coefficient. The storage coefficient is a measure of the amount of water stored in an aquifer for a unit rise in the elevation of the piezometric head. For an unconfined aquifer, the storage coefficient (or specific yield) determines the rate of change in elevation of the water table. Values of this parameter can be estimated, crudely, from a knowledge of the soil material. However, the most reliable estimates of formation storage coefficients are usually determined from aquifer performance tests.

H&H PROCESSES. The primary H&H processes that influence wetland groundwater interaction are precipitation, infiltration, groundwater discharge/recharge, shallow and deep groundwater flow, groundwater pumping, and evaporation and transpiration. A schematic showing the relationship between these processes is shown in Figure 1.

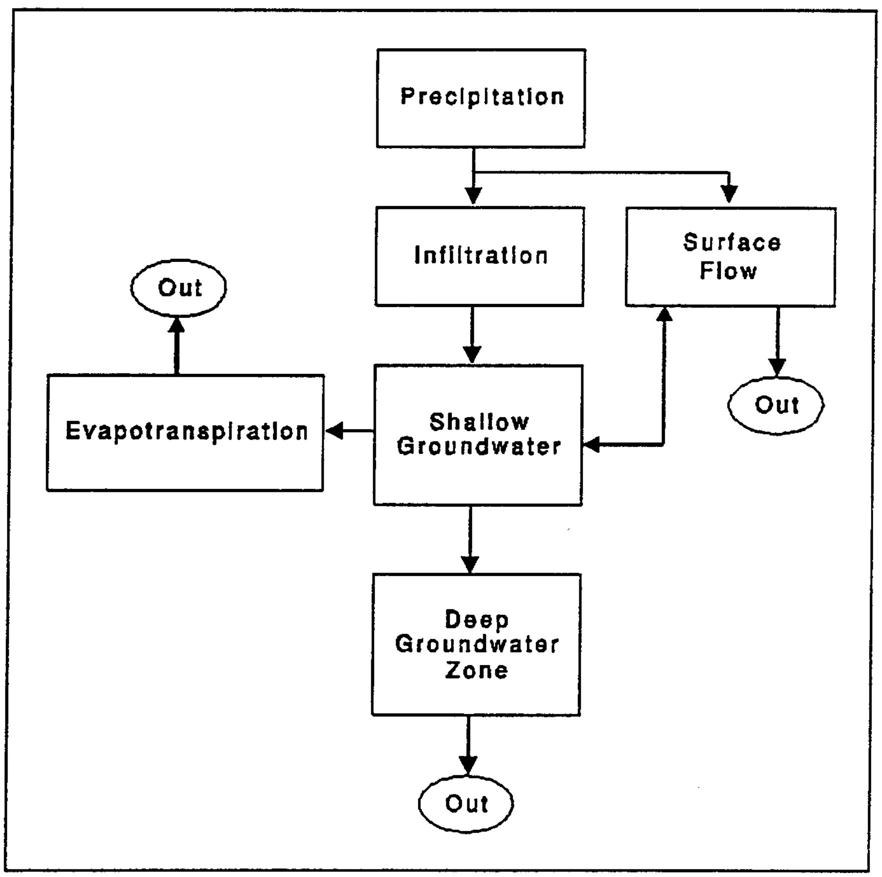

Figure 1. Flowchart of groundwater H&H processes

- Precipitation. Groundwater processes associated with wetlands result from local and regional precipitation patterns. Precipitation can influence a wetland water budget directly through rain and snowfall within the physical boundaries of the wetland, or indirectly through inflows from upstream watersheds. Information required to estimate the influence of precipitation ranges from the regional and seasonal variability to the frequency and magnitude of individual storm events. Complete daily records and statistical summaries of regional meteorological conditions are available through the National Weather Service.

- Infiltration. In areas where the surface water is not in direct hydraulic contact with the groundwater, surface water moves generally vertically downward through the unsaturated zone to the saturated zone (i.e., water table), or a perched water level above an impervious soil layer. The infiltration rate is governed by a number of factors, including the depth of surface water, the initial soil moisture content, and soil properties such as hydraulic conductivity. Infiltration and subsequent groundwater recharge are generally more important for upland and depressional sites, where stream inflows may not be the major factor creating the wetland. Sites with low-permeability soils may result in overland flow to the wetland or stream, whereas high-permeability soils can lead to significant infiltration to the underlying groundwater system. Where significant infiltration exists, a rapid increase in the elevation of the local water table can occur. This situation is most likely near streams or depressional wetlands, where the surrounding water table is near the ground surface and the residual moisture content high. The resulting high gradients from the groundwater system to the stream or wetland can cause significant groundwater discharge. Infiltration rates are estimated by direct measurements such as percolation tests and analytic methods (Chow 1964).

- Groundwater Discharge and Recharge. Groundwater discharge occurs where the elevation of the water table (piezometric surface) exceeds that of the surface water. Groundwater recharge results when the opposite occurs. Estimates of the rate of groundwater discharge or recharge can be obtained by applying Darcy's Law. The data required for this evaluation are synoptic surface water elevations, groundwater elevations or piezometric heads, and the hydraulic conductivity of the soil or sediment. At some sites, for example within the Prairie Pothole region, the deposition of organic material in the permanent pool may significantly reduce the local hydraulic connection to the groundwater system. However, hydraulic conductivities in the adjacent areas may be significantly larger, and become important as the water level in the wetland rises. In addition, wetlands have been observed to change seasonally from discharge to recharge or flow-through systems. As a result, it is important to examine both the spatial and temporal variability of wetland groundwater characteristics.

- Shallow Versus Deep Groundwater Flow. The interaction between the shallow groundwater zone and the underlying regional groundwater system can influence the rate of shallow groundwater transport, and thus the interaction with surface waters and wetlands. In some systems, an aquitard (i.e. confining layer) exists that decouples the shallow and deep groundwater zones. In these cases it is important that local shallow-water well piezometric heads (as opposed to regional groundwater data) are used to assess wetland groundwater function. On the other hand, hydraulically coupled aquifers can exhibit upward or downward flow depending on the relative piezometric heads and spatial variations in soil and sediment properties. The potential influence of the deep groundwater zone can be examined by inspecting available stratigraphic information for evidence of aquitard material or other significant changes in formation composition. This process can be further examined utilizing measurements of head from shallow piezometers and deep wells to develop piezometric contours of the system.

- Groundwater Pumping. Groundwater pumping or pump-recharge can influence groundwater processes in the vicinity of a wetland by altering the piezometric surface, and thus hydraulic gradients. Evidence of pumping can be seen in piezometric contours, or records obtained from agricultural extensions, Geological Surveys, and the Departments of Health or the Environment. In areas where pumping is used for irrigation, pumping is often seasonal, and the effects on shallow groundwater movement can vary. In addition, irrigation supported by deep-water well pumping may increase infiltration to near-surface aquifers.

- Evaporation and Transpiration. Evaporation from the groundwater zone occurs only when the water table is within a few inches of the ground surface. Evaporative losses depend on meteorological conditions such as air temperature, humidity, and wind speed, ground conditions such as vegetative cover, and the soil moisture content.

  Transpiration results from root uptake by emergent plants and the subsequent loss through leaf surfaces. Over extended dry periods, transpiration can cause the water table to decline as far as the deep root zone of the wetland vegetation. Estimates of transpiration rates are related to meteorological conditions, vegetation characteristics, soil moisture content, and the depth to the deep-root zone. These data are available through state agricultural extension offices.

  Often the effects of evaporation and transpiration on a wetland water balance are combined into a single estimate of water loss called evapotranspiration (ET). In depressional wetlands, where there is no significant outlet, and in wetlands where the water table is often close to ground surface, ET may be the most significant factor in removing water from the system. A number of methods for estimating potential or actual evapotranspiration at the ground surface are presented in the literature (Christiansen 1968; Kadlec, Williams, and Scheffe 1986).

CONCLUSION: This technical note provides a framework for examining groundwater processes within a wetland. The information and supporting references presented can be used by field personnel as a guide to (1) identifying the H&H processes that significantly influence wetland function, (2) understanding the interrelationships among the various H&H processes, and (3) identifying the data required to determine the relative importance of individual H&H processes. In general, the overview provided in this technical note should be used to avoid the possible omission or misinterpretation of specific H&H mechanisms and their role in determining the overall water budget of a wetland.

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WRP Technical Note HY-IA-3.1
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Installing Monitoring Wells/ Piezometers in Wetlands

PURPOSE: Wetland regulatory personnel frequently need quantitative information about shallow hydrologic regimes of wetlands and adjacent uplands. Monitoring wells and piezometers are some of the easiest instruments to use to determine depth of shallow water tables. Most of the literature on piezometers and monitoring wells, however, deals with installation to greater depths than needed for wetland regulatory purposes. This technical note describes methods of construction and installation of monitoring wells and piezometers placed at depths within and immediately below the soil profile using hand-held equipment.*

DIFFERENCE BETWEEN SHALLOW MONITORING WELLS AND PIEZOMETERS: Monitoring wells and piezometers are open pipes set in the ground. They passively allow water levels to rise and fall inside them. The difference between a monitoring well and a piezometer is where along the pipe water is allowed to enter (length of perforated area).

Shallow monitoring wells allow penetration of water through perforations along most of the length of the pipe below ground. Therefore, the water level in a monitoring well reflects the composite water pressure integrated over the long, perforated portion of the pipe. This kind of well sometimes is called an "open-sided well," "observation well," or a "perforated pipe."

Piezometers allow penetration of water only at the bottom of the pipe, either directly into the bottom or along a short length of perforation near the bottom. Consequently, the water level in a piezometer reflects the water pressure only at the bottom of the pipe. Piezometers are sometimes called "cased wells."

The difference between monitoring wells and piezometers is significant because monitoring wells generally extend through more than one water bearing layer and therefore cannot be used to detect perched water tables, whereas piezometers can. Water pressures in the soil vary in response to several factors, including depth, differential permeability of strata, and water flow. These different factors can be isolated and interpreted independently with groups of piezometers. These factors cannot be differentiated with a monitoring well because different water pressures are intercepted at many depths within the same instrument and cannot be sorted out.

SELECTING INSTRUMENTATION: Before installing instruments, it is vital to define study objectives to avoid gathering unnecessary or meaningless data.

To investigate when a free water surface is within the top foot or two of the soil, 2-ft deep monitoring wells are sufficient. Deeper instruments are not necessary and may yield misleading information if improperly chosen and situated.

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* The methods described herein do not apply to water-sampling studies. Researchers needing to sample water from wells should refer to U.S. Army Corps of Engineers Document EM 1110-7-1(FR): Monitor Well Installation at Hazardous and Toxic Waste Sites and ASTM D5092-90: Design and Installation of Ground Water Monitoring Wells in Aquifers.

When trying to characterize water flows into and out of a wetland or differences in water pressure of soil horizons, clusters or "nests" of piezometers are needed. Most mitigation and evaluation studies require nests of piezometers with instruments located at depths ranging from a couple to many feet. Each piezometer in a nest should be installed at the same surface elevation and within a couple meters of the others. This arrangement allows answering questions about ground-water discharge and recharge, direction and rate of water flow, and water flow in different strata.

Zones of possible perching or water flow must be identified after study objectives are determined. This requires soil profile descriptions to the depth of interest -- often 6 to 10 ft. The profile descriptions should include horizon depths and information from which significant differences in permeability can be inferred: texture, induration, and bulk density.

If only shallow monitoring wells are used, they should be placed above the first slowly permeable horizon that could potentially perch water. Piezometers, on the other hand, should be installed both above and below horizons of low permeability to verify perching. Sand strata should also be monitored. Instruments should not be located at uniform depths around a study area unless the soils are uniformly stratified.

Typical well configurations include a shallow monitoring well through the A and E soil horizons and piezometers in the B horizon and C horizons. Deeper piezometers are often included, particularly if there are significant changes in grain size distribution in the lower soil profile. Soil studies usually include piezometers to 80 inches, the arbitrary lower depth of soil characterization in most parts of the country. Soil profile characteristics are available from the USDA Soil Conservation Service.

CONSTRUCTION OF PIEZOMETERS AND SHALLOW MONITORING WELLS: Monitoring wells and piezometers consist of four parts. Starting from the bottom and working up, these are (1) the well point, (2) the screen, (3) the riser, and (4) the well cap (Fig. 1). Other items that may be used in installation include (5) sealant to prevent water flowing along the sides of the pipe, (6) sand to ensure hydrologic contact and to filter out fines that move toward the well, (7) filter sock of geotextile to further filter out fine materials, and (8) concrete protection pads.

- The well point keeps soil from entering the well from the bottom. This may happen by sloughing during periods of high hydraulic head, particularly in sands and highly dispersive soils. Well points are bought separately if the wells are constructed of PVC pipe. One should drill holes or saw a slit in the bottom of a commercially manufactured well point to prevent the closed well point from holding water and giving false readings during drought.

- The screen allows water entry into the sides of the pipe. In shallow monitoring wells the screen extends from the bottom of the pipe to within 6 in. of the ground surface. In piezometers, the screen is the perforated end of the pipe, usually 6-12 in. in length.

  Commercially manufactured PVC well screen consists of finely slotted pipe. Screen with 0.010-in. width slots is adequate for most situations. In dispersive soils with high silt contents one should use 0.006-in. slots and a sand pack of 40-60 mesh silica sand.

  The slot size of the well screen should be determined relative to the grain size analysis. In granular non-cohesive strata that will fall in easily around the screen, filter packs are not necessary. The slot size should retain at least 90-99% of the filter pack (ASTM D-5092-90).

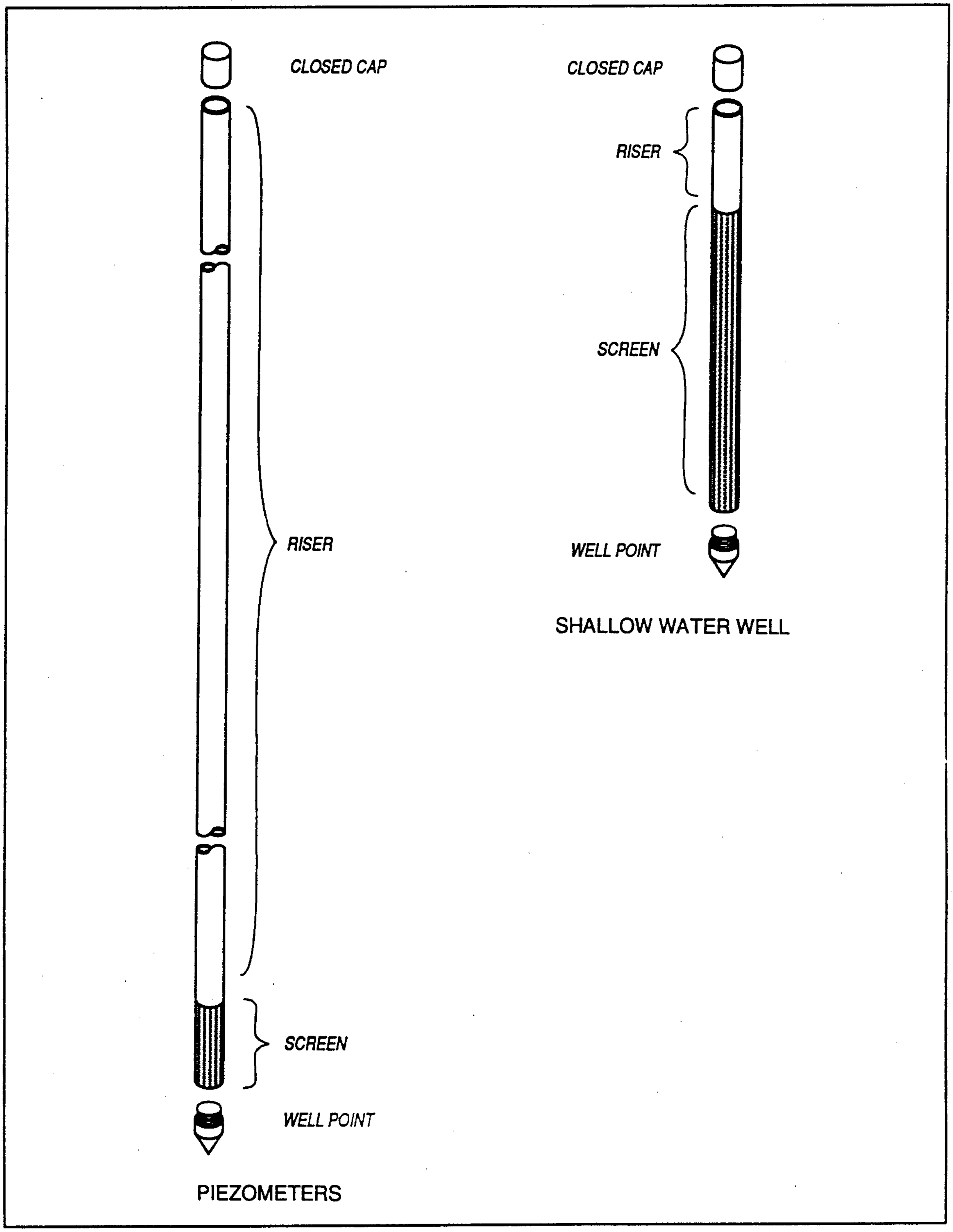

Figure 1. Parts of piezometers and shallow monitoring wells

- The riser is unslotted pipe that extends from the top of the screen through the ground surface and into the air to allow monitoring access. Riser of PVC is sold separately from the screen in 2 to 15 ft lengths. Sections of PVC riser may be screwed together to extend the riser to the length desired.

  The diameter of pipe used in piezometers and shallow monitoring wells depends on the purpose of the well and monitoring devices used. Pipes with an inside diameter (ID) of 1 in. or less are preferred. Small water samplers and automatic monitoring devices are available to be used in the small diameter pipes. If not, larger diameter pipe will be necessary, the size depending on method of sampling or monitoring.

  In shallow monitoring wells the riser should extend from 6 in. below the ground surface to the top of the pipe above ground. In piezometers the riser extends from the monitoring depth to the top of the pipe. Height above the ground surface depends on local needs such as visibility and access. Shallow pipes should not be extended more than a couple feet above the ground surface because of the great leverage that can be applied to the above-ground riser.

- The well cap is placed on top of the pipe to protect the well from contamination and rainfall. Well caps should fit tightly enough that animals cannot remove them and should be made of material that will not deteriorate with exposure to the elements. Threaded PVC caps meet these requirements in commercially bought wells.

  Well caps can be easily constructed from PVC pipe of larger inside diameter than the outside diameter of the piezometer. The larger ID pipe is cut to 6-in. lengths; one end of the 6-in. cylinder is then closed by gluing on an appropriately sized PVC cap (Fig. 2). Inverted plastic bottles or tin cans should not be used because of the ease with which they can be removed by animals or wind and because many such objects rust, degrade in sunlight, or break when frozen.

  Well caps should allow air pressure inside the pipe to equalize with that outside. Some PVC well caps are manufactured to allow air passage through a joint. Others should be modified so they cannot be threaded on tightly; this modification can be accomplished by closing the lower part of the threads with a bead of epoxy. If a vent hole is drilled in the side of the riser it should be too small for wasps to enter.

  After reading, well caps should not be secured so tightly that the shallow pipe must be pried and jostled to remove the cap. If surface water may overflow the tops of the pipes, caps should be secured so they will not be lost.

- Sealant is placed above the sand filter. This prevents water flow along the sides of the pipe from the ground surface and through channels leading to the pipe. If the well screen is below the water table at time of installation, the annular space above the sand is filled with bentonite to the top of the water table; grout is used to fill the annular space above the water table and to the soil surface. If the well screen is above the water table, at least 6 in. of bentonite is placed above the sand filter and grout is filled in above it.

  Bentonite is available in either powder or pellet form from well drilling companies. Pellets are easier to use in the field. Fine pellets can be dropped directly down the annular space above the sand filter. If this zone is already saturated with water, the pellets will absorb water in place, swell tight, and seal off the sand filter from the annular space above. If the bentonite pellets are

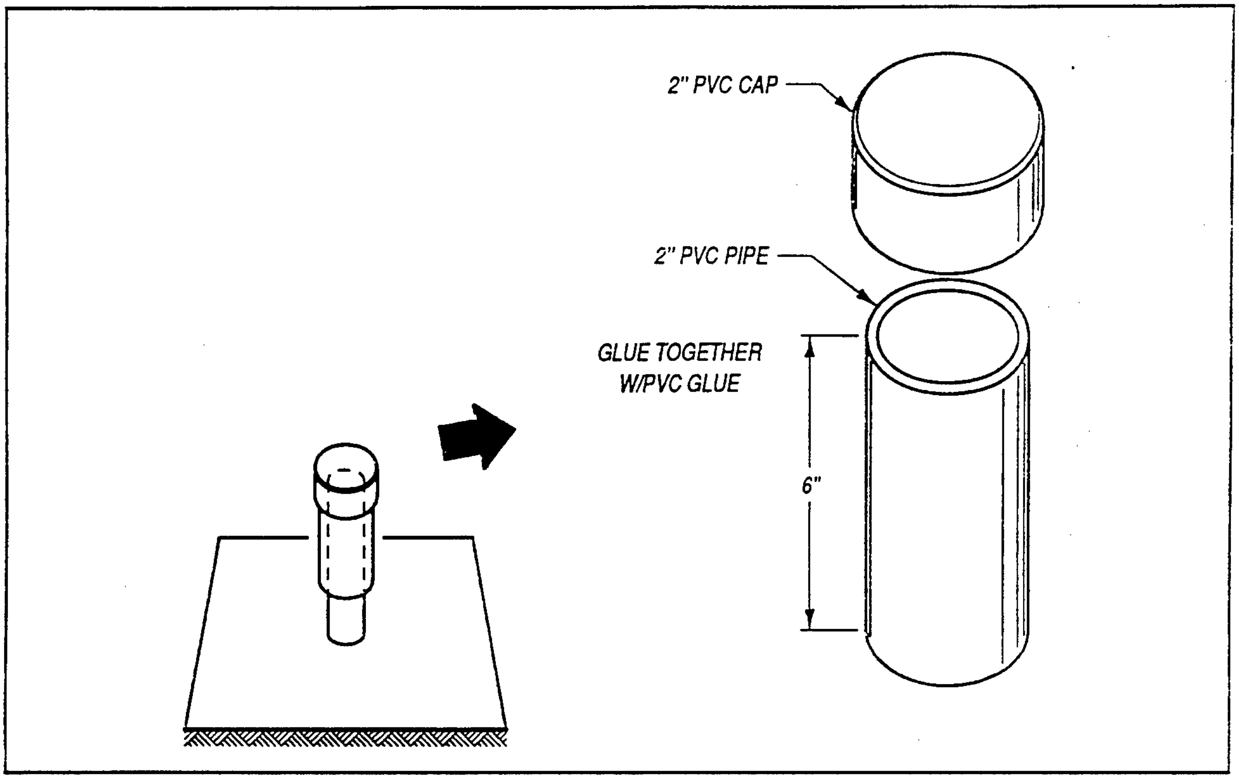

Figure 2. Homemade cap made of oversize PVC piping

dropped into a dry annular space it is necessary to drop water down, too, so the pellets can swell shut. The purpose of the bentonite collar is to prevent grout from flowing into the sand filter.

After the bentonite has been installed, grout is mixed and dropped down the remaining annular space up to the soil surface. The recipe for grout is 100 pounds of #2 Portland cement, 5 pounds of bentonite powder, and 7 gallons of water. The grout provides the primary protection from side flow down the riser because (1) it penetrates the surrounding soil matrix better than bentonite and (2) it does not crack during dry seasons.

- Sand is placed around the entry ports of the screen. Clean silica sand is commercially available from water-well supply houses in uniformly graded sizes. Sand that passes a 20 mesh screen and is retained by a 40 mesh screen (20-40 sand) can be successfully used with 0.010-in. well screen; finer sized 40-60 grade sand is appropriate for use with 0.006-in. screen. If available, the finer sand and screen should be used to pack instruments in dispersive soils with silt and fine silt loam textures.

  ASTM-5092-90 recommends that primary filter pack of known gradation be selected to have a 30% finer (d-30) grain size that is about 4 to 10 times greater than the 30% finer (d-30) grain size of the hydrologic unit being filtered. Use a number between four and six as the multiplier if the stratum is fine. This recommendation may not be achieved in clayey soils, in which case filter socks should be used.

- Filter socks are tubes of finely meshed fabric that can be slipped over the screened end of a well to filter out silt and clay particles that may be carried toward the pipe in flowing water. These should be used in conjunction with sand packs in highly dispersive soils. Filter socks are available from engineering and water-well supply houses. Results of multi-year studies indicate that geotechnical fabric may clog up with microbial growth. In long term projects, filter socks must be monitored.

- Protective concrete pads are often poured around the pipe at the ground surface. They serve two purposes: (1) if large enough, concrete pads can prevent run-off water from channeling down the sides of the pipe, and (2) in many states they are required on all water wells to protect sources of drinking water from contamination.

  Accurate ground-water monitoring requires that instruments be isolated from incursion of surface run-off down the sides of the pipe. A large sloped concrete pad (3 or more feet in diameter) will usually prevent run-off from collecting around the pipe and preferentially running down it. However, water channels can develop underneath hastily installed concrete pads. Poorly constructed concrete pads will crack as the soil underneath settles or heaves with shrink/swell and freeze/thaw cycles. Installation of a tamped and wetted bentonite sleeve around the pipe and proper mounding of soil around the base of the riser at the ground surface will prevent side-flow more effectively than an improperly constructed concrete seal.

  Some states require that all monitoring wells be isolated from surface flow with a concrete pad. This regulation is intended to protect drinking water sources from pollutants in surface run-off. State regulations should be observed at all sites despite the inconvenience of transporting materials to remote locations. A copy of the state's water well regulations must be obtained and proper forms for each pipe must be filed. For shallow instruments that are many meters above aquifers or aquifer recharge zones it is recommended to consult with the appropriate state agency for an exemption. Most of the time common sense will prevail and such pads may be omitted from the design of very shallow wells.

INSTALLATION OF SHALLOW MONITORING WELLS AND PIEZOMETERS:

- Shallow Monitoring Wells. Installation method is for 2-ft deep monitoring wells.

  Uses: Shallow monitoring wells may be used to determine when the shallow free-water surface is within depths required by jurisdictional wetland definitions. These depths have historically varied from 0.5 to 1.5 ft and are shallower than the shallowest slowly permeable zone in most soils. Therefore, 2-ft deep monitoring wells are sufficient to detect water tables in most soils if the only information needed is whether a jurisdictional wetland is present. To know how much the water table fluctuates during the year at least one deeper piezometer should be installed next to the shallow monitoring well. Deeper wells with 3 or 4 foot screens require that horizons have similar permeabilities.

  Construction: Shallow monitoring wells used for wetland jurisdictional determinations should have 1.0-1.5 ft of well screen. Enough riser should be added above the screen to allow 0.5 ft of riser below ground and 0.5 to 1.0 ft of riser above ground. The above-ground portion of the riser should be kept to a minimum to protect the surface seal from disruption during accidental jostling. A vented well point should be added to the bottom of the screen and a well cap to the top of the riser.

  The total length of the instrument will be approximately 3 ft: 1.5 ft of screen, 0.5 ft of riser below ground, 0.5 ft of riser above ground, and 0.5 ft of well point and cap. The well should be constructed of 1-in. ID PVC pipe with threaded joints unless water sampling or automatic monitoring devices require wider pipe.

Installation: A shallow monitoring well should be installed by (1) auguring a 2.5-ft deep hole in the ground with a 3-in. bucket auger, (2) placing 6 in. of silica sand in the bottom of the hole, (3) inserting the well into the hole with the vented well-point into but not through the sand, (4) pouring and tamping more of the same sand in the annular space around the screen -- this should be at least 6 in. below the ground surface, (5) pouring and wetting 2 in. of bentonite above the sand and (6) pouring grout to the ground surface. A final mound of grout prevents surface water from puddling around the pipe unless a concrete pad is required. Installation is illustrated in Figure 3.

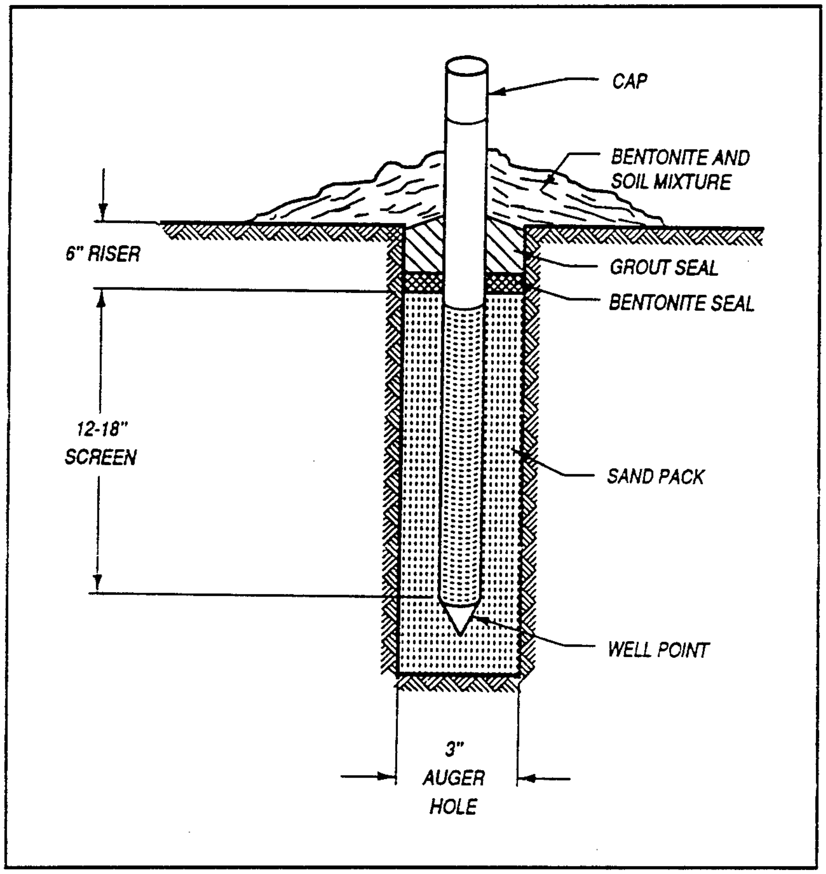

Figure 3. Shallow monitoring well

- **Standard Piezometers.** Installation method is for standard piezometers.

Uses: Standard piezometers are the preferred instrumentation for monitoring water tables. This method should be used whenever results may be published or litigated. Even in most jurisdictional studies involving shallow monitoring wells, a few standard piezometers should be installed around the project site to learn how deep the water table drops during the dry season.

Construction: Standard piezometers consist of 0.5-1.0 ft of screen, enough riser to extend above the ground, well cap, and vented well point. The total length of the piezometer will depend on the depth of the zone being monitored. Pipe diameter should be one inch unless sampling or monitoring instruments require wider pipe.

Installation: Installation of a standard piezometer entails (1) auguring a 3-in. diameter auger hole to a depth of 6 in. greater than the below-ground length of the piezometer; (2) dropping and tamping 6 in. of sand into the bottom of the augured hole; (3) inserting the well-point and pipe into the sand; (4) tamping sand around the length of the screen and 6 in. higher along the riser, (5a) if the sand filter is below the water table, pouring bentonite pellets into the annular space from the sand filter up to the water table, or (5b) if the sand filter is above the water table, pouring bentonite pellets at least 6 in. above the sand filter and wetting with water; and (6) pouring

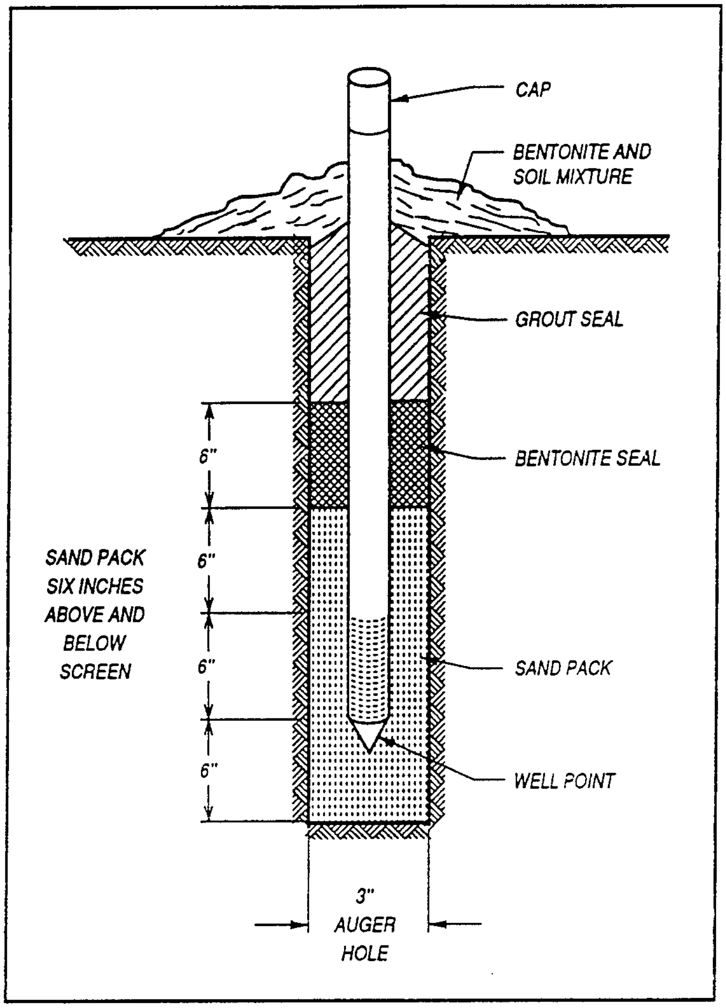

Figure 4. Standard piezometer

grout down the remaining annular space to the ground surface (Fig. 4).

The diameter of the auger hole should accommodate the pipe and an annular space of at least 1 in.; this will allow sufficient room to tamp in sand and pour bentonite without risking cavities in the sealant. The part of the hole that will be occupied by sand should be scarified if the soil is moist and smeared by the auger.

In deep sandy soils the bentonite and grout sleeves are not necessary because water flows through the entire soil matrix almost as quickly as down the sides of the pipe. The annular space around the riser is simply backfilled with sand that was removed during auguring. If the natural sand is fine enough to enter the slots of the piezometer, a sleeve of 20-40 grade sand should still be installed around the screen. If a less permeable layer is intercepted -- for instance, a spodic horizon -- that layer should be sealed with bentonite.

- Equipment Needed. Equipment needs will vary with depth and diameter of piezometers to be installed. The following is a list of equipment necessary for installation of shallow monitoring wells and standard piezometers to depth of 10 ft or shallower.

PVC well screen, riser, well points, and caps
bucket auger 2 in. wider than the OD of the pipe
auger extensions
pipe wrenches for auger extensions
tamping tool (0.5-in. thick lath 2 ft longer than the deepest well works well for wells up to 4 ft deep; 0.5-in. diameter metal pipe is necessary for deeper wells)
bentonite pellets
#2 Portland cement and bentonite powder (100/5 ratio)
bucket for mixing grout
water for grout and bentonite
silica sand
steel tape long enough to measure deepest hole
permanent marking pen to label pipes
concrete mix, water, wood forms, etc., for construction of concrete pads, if required

- Checking for Plugged Pipes. After the pipe has been installed it is necessary to assure that it is not plugged. For pipes installed above the water table fill the pipe with water and monitor rate of outflow; for pipes installed below the water table pump the pipes dry and monitor rate of inflow. If the screens are plugged one should re-install the pipes. This test should be performed every few months throughout the study.

READING WATER LEVELS: Numerous methods have been devised for reading water levels in shallow piezometers and wells. The simplest method is to mark a steel tape with a water-soluble marker and insert the tape to the bottom of the well. The only equipment needed with this method is the tape, marker, and a rag to wipe the tape dry after reading.

Other methods involve use of various devices at the end of a flexible tape. All suffer from the lesser accuracy obtained with a flexible tape rather than a rigid one. Most also suffer from inconvenience or complexity. Some of the variations are: (1) floating bobs on the end of a flexible tape (these must be calibrated to correct for length of the float and for displacement of water); (2) electric circuits that are completed when a junction makes contact with water; and (3) devices that click or splash when a flexible tape is dropped down the well (there is always uncertainty about the exact depth at which the noise was heard).

Water levels may also be monitored continuously with down-well transducers and remote recording devices. These cost around a thousand dollars per well but may be necessary for some study objectives. Automatic recording devices may pose special limitations on pipe diameter or construction, so the recording instrumentation should be investigated before pipe is bought. Because automatic devices may be re-used in many studies, cost estimates should be prorated over their expected life rather than assigned only to one study. If study objectives require frequent readings at remote sites an automatic recording device may be the only option available.

One method of reading water levels that should be avoided is insertion of a dowel stick down the pipe. Dowels displace enough water to give significantly false readings, particularly if the pipe has a narrow diameter and the dowel is inserted the entire length of the pipe. A steel tape also displaces water, but not enough to cause significant error.

When reading water levels height of the riser above the ground surface should be noted. Monitoring wells and piezometers may move as much as 3 in. in a season in clayey soils that undergo wet/dry or freeze/thaw cycles.

Frequency of reading will depend on study purposes. When determining consecutive days with water tables at a particular depth for wetland delineation purposes, daily readings may be necessary once the "growing season" starts. Daily and even hourly readings may be necessary to monitor tidally influenced wetlands. Longer term studies are usually adequately served with biweekly readings during most of the year and weekly readings during periods of water-table rise or draw-down. Long breaks between readings may cause ephemeral fluctuations due to intense storms or floods to be missed. If the study is important enough to be published or litigated, readings should be frequent and regular.

SOURCES OF ERROR: The following are significant sources of error with piezometers and monitoring wells: (1) side-flow down the riser, (2) plugged screens, (3) movement of pipes due to shrink/swell and freeze/thaw cycles, (4) water displacement during reading, (5) infrequent readings, (6) incorrect instrumentation, (7) pipes of too large a diameter, (8) faulty caps, and (9) vandalism.

- Side Flow. Erroneously high water heads can be recorded in piezometers and shallow monitoring wells if water is conducted to the screen faster than it normally would be through the soil. The most common source of this water is surface run-off channelled down the sides of the riser. It is critical that wells and piezometers fit snugly into the ground and that a collar of soil be mounded and tamped around the base of the pipe at the ground surface. This is the primary reason that the standard piezometer installation described here is preferred over simply driving the pipe into the ground; bentonite and grout seals are more secure than natural soil contacts along driven pipe.

  With piezometers, an additional source of error is subsurface water conducted to the pipe via cracks, root channels, or animal burrows. These problems will not be significant in all soils. When present, the only protection is an adequate sleeve of bentonite and grout around the riser.

  In montmorillonitic soils with high shrink-swell potential, one may never be able to eliminate cracks. In this case it may be necessary to auger soil samples from depth and determine water contents gravimetrically throughout the year. Such gravimetric determinations should certainly be made whenever false readings in piezometers are suspected.

- Plugged Screens. The slots or holes in screens may plug up, particularly in dispersive soils that are saturated for long periods of time. Algal growth can also plug up screens of instruments installed at biologically active depths. Plugged screens can give artificially dry readings during wet periods and artificially wet readings during dry periods. They will impede water flow so that fluctuating water tables can be missed even with frequent readings.

  Plugging of screens is most easily prevented by using an appropriately sized sand filter. One can check for such plugging by pumping wells dry on a regular basis and noting if they fill back up again.

  If shallow monitoring wells plug up, they should be re-installed. Deeper piezometers may be unplugged by pumping the wells dry several times and discarding the muddy water pumped out. If they continue to plug, they should be re-installed with 40-60 grade sand and 0.006-in. screen or with a filter sock.

- Movement of Pipes. Shallow pipes move much more than one would expect. Concrete collars can be lifted several inches above the ground in soils with clayey texture. This movement is caused by soil expansion during wetting or freezing. There is little one can do to prevent this, but one should monitor such movement by noting the height of the pipe out of the ground when reading water table depths.

  Pipes that move a lot and experience inundation as well probably no longer fit snugly in the ground and therefore experience side-flow down the riser. Gravimetric water contents should be checked whenever one suspects false readings due to side flow. If these problems persist, piezometers should be re-installed.

- Water Displacement. As mentioned previously, water levels in wells should not be read by inserting a dowel stick down the pipe. The dowel will displace its volume in water and thereby give an artificially high reading. A marked steel tape should be used instead.

- Infrequent Readings. A common source of error in many long-term studies is missed or post-poned readings. Before the study is started one should arrange for sufficient help to make readings on schedule and frequently enough to answer study questions. It is all too easy for professionals with many other responsibilities to delay a trip to the field because of intruding obligations. Yet, gaps in a data set will call an entire study into question. If budgets allow, automatic recorders may solve the problem.

- Incorrect Instrumentation. Piezometers are preferable to shallow monitoring wells for most questions more complicated than simple presence or absence of water tables in the rooting zone. Water levels in monitoring wells are composites of the hydrologic head at all depths intercepted by the well screen. Consequently, perched water tables will usually be misinterpreted if monitoring wells penetrate the drier substratum beneath.

  Readings from improperly placed piezometers can also be misinterpreted. Piezometers should not be placed at uniform and arbitrary depths without reference to soil horizon differences. Piezometers placed at arbitrary depths are likely to straddle horizon boundaries or entirely miss highly permeable horizons with significant subsurface flow.

- Large-Diameter Wells. Piezometers and wells should be as narrow as practical. The wider the pipe, the greater the volume of water that has to move in and out of it in response to changes in hydraulic head. Consequently, a large-volume monitoring well will respond more sluggishly than a small-volume well. This is more critical in soils with low permeability and for studies that require monitoring several times a week or shortly after major precipitation events.

  Most wells can be successfully constructed from 1 or 1.25 in. pipe. Use of 4 or 6 in. pipe should be avoided unless study conditions require the larger pipe. An excessively large annular space should also be avoided, for the same reasons.

- Faulty Caps. Commercially manufactured caps often fit too tightly on PVC riser, necessitating excessive force to remove them. The resultant jostling can disrupt the seal between the pipe and the sealant, allowing water flow along the side of the pipe. To avoid this, threaded caps -- if used at all -- should be screwed on the pipe loosely. Avoid caps made of materials that deteriorate and break in sunlight or frost, can be nudged off by animals, or blown off in the wind. Most such problems can be alleviated by use of home-made caps constructed as described in Figure 2.

- Vandalism. Often vandalism cannot be avoided. Three approaches to the problem are (1) to hide the wells, (2) to shield them, and (3) to post them and request they not be disturbed. Simple signs stating "Ground-water pipes: please do not disturb" have been used successfully. In some communities it may be better to hide the pipes. Padlocks may keep out the curious. A second and larger pipe surrounding the above-ground portion of the monitoring well may offer protection against gunshot. Still, pipes probably cannot be protected from the malicious. Extra equipment should be bought at the beginning of a project so that vandalized wells can be replaced.

INTERPRETING RESULTS: As mentioned previously, data from shallow monitoring wells are ambiguous unless the well is very shallow (2 ft or less), or the soil is highly permeable or unstratified. A 4-ft deep well that traverses a profile of A-E-Bt-C is likely to miss the slightly perched water table that rests on top of the Bt and in the E. The most permeable horizon contributes the most water to a water well. If the bottom of the well intercepts an unsaturated horizon of higher permeability, then water can actually be wicked away from the well.

Piezometric data can also be confusing unless one is familiar with principles of water flow. If water is static in unstratified soil, water levels in all piezometers should be the same (Fig. 5). However, if

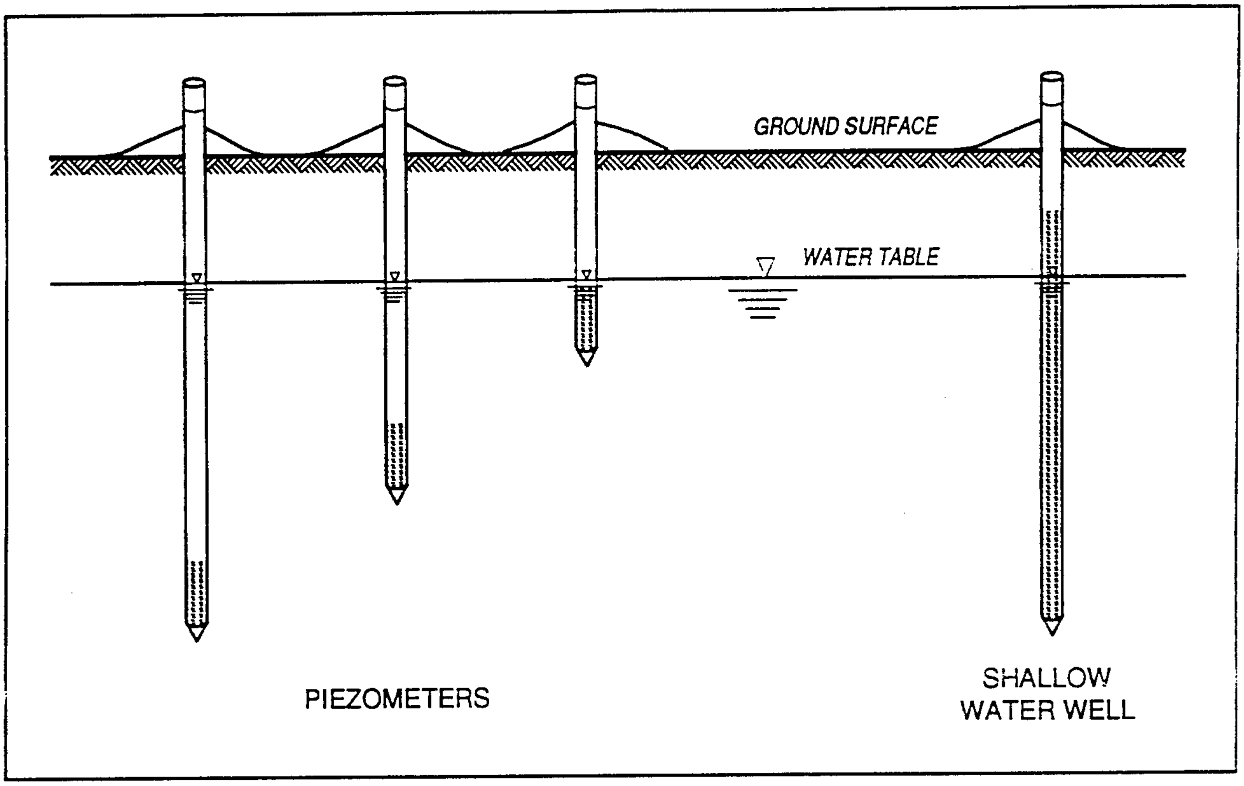

Figure 5. Instruments in unstratified materials with static water-table

differentially permeable strata are present or if water is moving up or down the soil profile, then piezometers will record different water levels at different depths.

A perched water table can be inferred from higher piezometric levels in the A or E horizon than the C (Fig. 6). For soils of uniform permeability, downward water movement (aquifer recharge) can be inferred from higher piezometric levels high in the soil and lower piezometric levels low in the soil (Fig. 7). Upward water movement (aquifer discharge) can be inferred from lower levels high in the soil and higher levels low in the soil (Fig. 8). Water moves from a zone of high pressure to a zone of low pressure, even against gravity, if the pressures are great enough. Proper interpretation of data requires some knowledge of soil horizonation and likely water sources.

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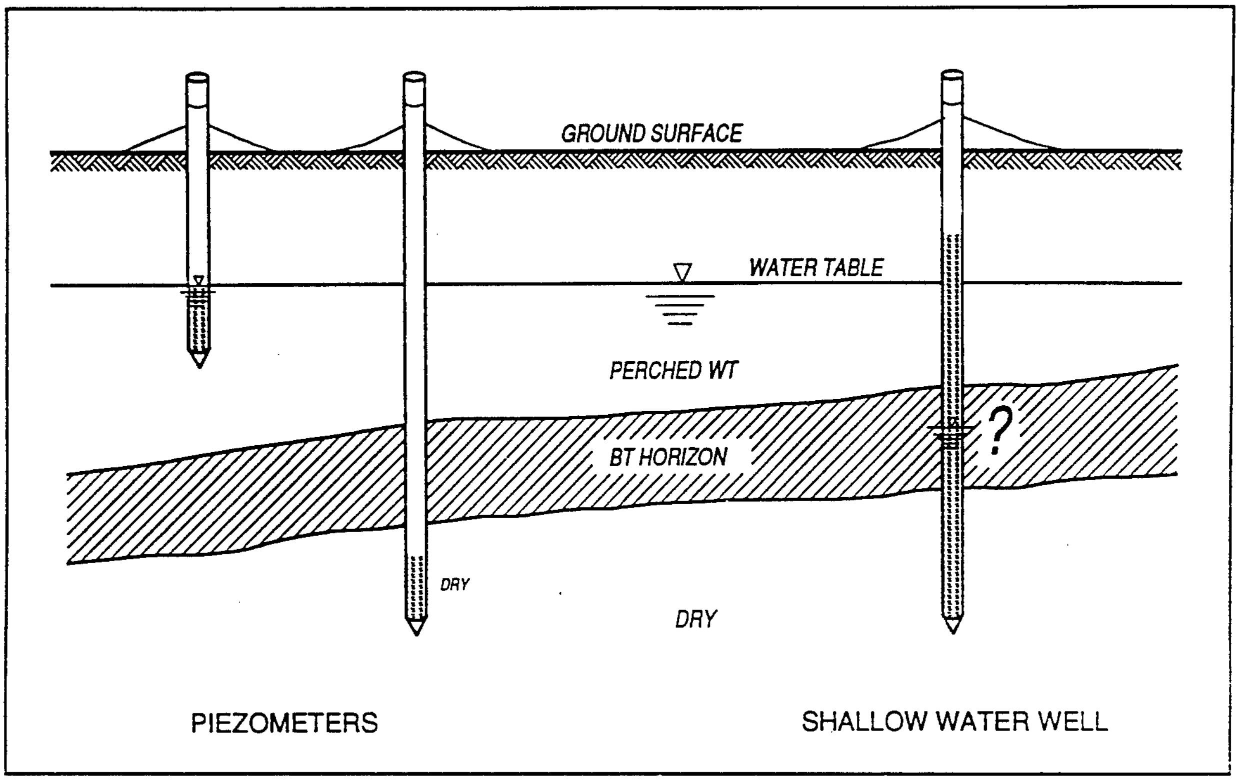

Figure 6. Monitoring instruments in stratified materials with perched water-table

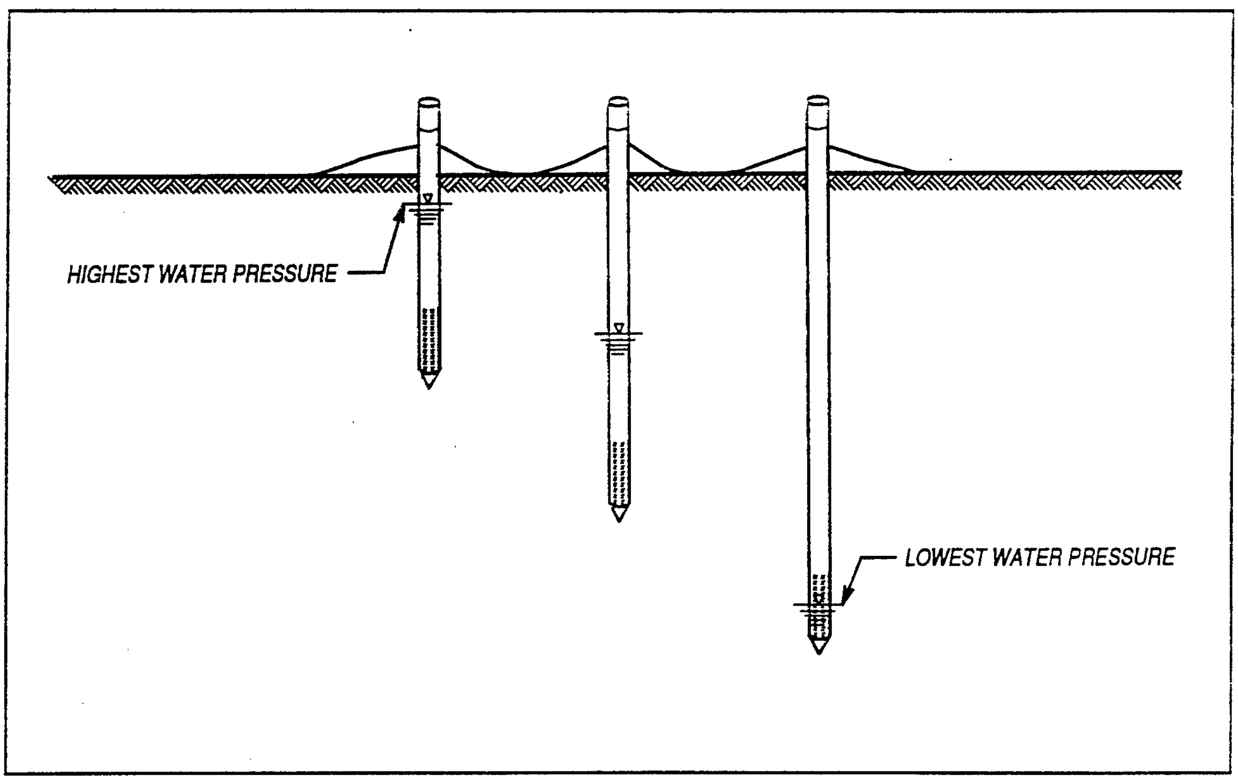

Figure 7. Recharge system with water flowing downward

APPENDIX B
Data Collection References

General

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