Regionalized Water Budget Manual for Compensatory Wetland Mitigation Sites in New Jersey

State of New Jersey
Department of Environmental Protection

Jon Corzine, Governor
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Disclaimer

In addition to describing technical aspects of the hydrologic budget and related considerations for wetland mitigation site design, parts of this manual describe specific recommendations and requirements for the preparation of water budgets for wetland mitigation sites in New Jersey. These recommendations and requirements are strictly a matter of NJDEP policy and do not necessarily reflect the policy or opinion of any other organization or contributor.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m^3/s)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per day (in/d)	0 .0254	meter per day (m/d)
	Evapotranspiration rate	

inches per day (in/d)	25.4	millimeter per day (mm/d)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
	Density	
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter (kg/m^3)

	Energy	
kilowatt hour (kWh)	3,600,000	joule (J)
kilowatt hour (kWh)	3.6	megajoule (MJ)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F=(1.8×°C)+32

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C=(°F-32)/1.8

Abstract

In New Jersey, wetlands are continually being threatened by competing land-use interests; therefore, successful wetland mitigation efforts—the compensation for wetland functions and values lost when wetlands are altered or converted to other land uses—are essential. The success of a mitigation project depends in large part on the selection of appropriate compensatory wetland mitigation sites. Adequate hydrologic characterization of a mitigation site is crucial to its success because hydrologic characteristics are the most important determinants of the successful **creation**[1], **restoration**, **enhancement**, and maintenance of jurisdictional wetlands. A wetland's water budget is an accounting of the balance between water inflows (precipitation, surface-water inflow, and ground-water inflow) and water outflows (**evapotranspiration**, surface-water outflow, and ground-water outflow); any difference between inflows to and outflows from a wetland represents a change in storage. A water budget serves as a valuable tool for understanding the hydrologic processes that occur in a given ecological system because it quantifies each of the individual components of a wetland's hydrologic cycle, and provides insight into the effects of potential or planned changes to the system.

This manual is a guide to facilitate the preparation of a water budget for compensatory wetland mitigation sites in New Jersey. It presents information on specific data sources and methods that are useful for the evaluation of hydrologic characteristics of wetlands in New Jersey, and is intended to increase the effectiveness of future mitigation efforts.

[1]Words in bold are defined in the glossary at the end of this report.

Introduction

Wetland mitigation refers to the compensation of **wetland functions** and **wetland values** that are lost when wetlands are altered or converted for other land uses. The purpose of wetland mitigation is to replace vital wetland functions including, but not limited to, floodwater storage, water-quality protection, and wildlife habitat through the enhancement of existing wetlands, the restoration of former wetlands, or the creation of new wetlands. A review of 90 freshwater wetland mitigation sites in New Jersey revealed that, on average, only about one-half of the area of all mitigation sites reviewed can be characterized as wetlands (Amy Greene Environmental Consultants, Inc., 2002). This review also indicated that the primary reason for the failure of wetland mitigation projects is improper hydrologic characterization, likely the result of an inadequate assessment and understanding of hydrologic conditions prior to site work. A review of proposed designs for these wetland mitigation projects found that most, in fact, failed to incorporate any assessment of available hydrologic information.

The State of New Jersey has identified the need to improve the hydrologic characterization of proposed wetland mitigation sites in order to develop reasonably representative site-specific water budgets for compensatory wetland mitigation projects. Therefore, the New Jersey Department of Environmental Protection (NJDEP), with input from the U.S. Geological Survey (USGS) and experts in the field of wetlands design, developed a manual that contains information on selected hydrologic parameters measured in New Jersey, as well as methods for using this information to evaluate the hydrologic conditions at a site. This manual can be used by wetland mitigation designers to aid in developing site-specific water budgets and preparing wetland mitigation proposals, and by the NJDEP in the evaluation of these proposals.

Purpose and Scope

This manual provides information to help improve the effectiveness of compensatory freshwater wetland mitigation projects in the State of New Jersey. The focus of the manual is the evaluation of sites that may be selected for conversion to wetlands in order to compensate for the destruction of natural wetlands. In particular, non-tidal wetlands are examined because their water balances are not dominated by the regular ebb and flow of tides. Also, attempts to construct non-tidal wetlands historically have not been successful in meeting wetland criteria set by the State of New Jersey, in part because the presence of hydrologic conditions required to maintain constructed wetlands was not adequately assured prior to construction. The information provided in this manual is intended to assist wetland mitigation designers in understanding hydrologic conditions in various New Jersey landscapes, locating and acquiring hydrologic data relevant to project sites within New Jersey, and conducting an adequate hydrologic evaluation through the development of site-specific water budgets. Organizations and online sources with available data on the components of the wetland hydrologic budget--precipitation, surface water, ground water, and evapotranspiration--are provided, as are methods for on-site data collection. In addition, various methodologies for determining the inputs to and outputs from wetland water budgets are described. Also presented is an example of a water budget for a hypothetical mitigation site in New Jersey.

Acknowledgments

This manual was developed through funding provided by the Wetlands Program of the U.S. Environmental Protection Agency (USEPA). The primary authors of the manual were Jason Lewis and Christine Wieben of the USGS, New Jersey Water Science Center. Virginia

Kop'Kash, Jill Aspinwall, and Jo Dale Legg of the NJDEP, Division of Land Use Regulation, assisted in the writing, editing, and oversight of the development of this manual by providing input and expertise on the compensatory mitigation process and information on historical mitigation projects for review and analysis. Bob Nicholson of the USGS, New Jersey Water Science Center, is gratefully acknowledged for assisting in the writing of the manual and for providing guidance and expertise, particularly in the areas of geohydrology and numerical modeling.

The fundamental concepts of this manual were based on "Planning hydrology for constructed wetlands" by Gary J. Pierce. A panel of experts in the field of wetlands site design in New Jersey provided critical input to this manual and helped to identify the models presented as well as the methods and requirements presented within this document. The members of the panel included Peter Kallin of Rutgers Cooperative Research and Extension; Douglas Freese of Amy S. Greene Environmental Consultants, Inc.; Abdulai Fofanah, Jennifer Brunton, Ed Samanns, and Donald Stevens of The Louis Berger Group, Inc.; Mark Gallagher of Princeton Hydro; Fred Akers of the Great Egg Harbor Watershed Association; Michael Folli, John Serban, and Karl Dauber of Parsons Brinkerhoff; and Judith Burton and Peter DeMeo of the NJDEP, Division of Land Use Regulation.

Special thanks are extended to the personnel of The Louis Berger Group, Inc., Douglas Freese of Amy S. Greene Environmental Consultants, Inc., and Princeton Hydro for providing access to the data sources and methods they use to evaluate the hydrologic components of wetland systems.

Special thanks also are extended to the following people who provided a technical review of the manual: Joe Marchesani, NJDEP; Helen Rancan, New Jersey Geological Survey; Rich

Mogensen, EarthMark Companies; Brett Bragin and Ross Feltes, New Jersey Meadowlands Commission; and Gary Pierce, Froghome Environmental.

PART I: Background Information for Wetland Mitigation in New Jersey

This manual is divided into two parts. Part I presents background material that sets the stage for a general assessment of a site's hydrologic characteristics. Topics covered in the first part of the manual include wetland definitions, growing season, basic wetland hydrologic characteristics, geologic characteristics of New Jersey as they relate to hydrologic characteristics, wetland classification, and mitigation-site selection. The goal of the first part of the manual is to guide wetland designers to the types of information that should be considered during the initial assessment of the hydrologic factors that affect the site.

Wetland Definition and Regulation

Over the years, numerous wetland definitions have been developed for both scientific and regulatory purposes (Cowardin and others, 1979; Mitsch and Gosselink, 2000; Tiner, 2005). Scientific definitions provide a basis for wetland classification and inventory, whereas regulatory, or legal, definitions act to guide government jurisdiction. One regulatory definition of wetlands—used by the EPA and the US Army Corps of Engineers (USACE)—is found in Section 404 of the Clean Water Act, under which wetlands are deemed “waters of the United States” and are regulated as such. As jointly defined by the EPA (Federal Register, 1980) and the USACE (Federal Register, 1982):

> The term “wetlands” means those areas that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions. Wetlands generally include swamps, marshes, **bogs**, and similar areas.

This definition is reiterated in the 1987 Corps of Engineers Wetlands Delineation Manual. According to the USACE manual, wetlands exhibit the following hydrologic characteristics:

> The area is inundated either permanently or periodically at mean water depths less than or equal to 6.6 ft, or the soil is saturated to the surface at some time during the growing season of the prevalent vegetation (U.S. Army Corps of Engineers, 1987).

In a memorandum on modifications and clarifications to the USACE’s 1987 manual, wetlands were further defined based on the number of days saturated during the growing season:

> Areas which are seasonally inundated and/or saturated to the surface for a consecutive number of days for more than 12.5 percent of the growing season are wetlands, provided

the soil and vegetation parameters are met. Areas wet between 5 percent and 12.5 percent of the growing season in most years may or may not be wetlands. Areas saturated to the surface for less than 5 percent of the growing season are non-wetlands (U.S. Army Corps of Engineers, 1992).

The water table is often used as an indicator of saturation. However, saturated soils typically are closer to land surface than is the water table as a result of the **capillary fringe** (U.S. Army Corps of Engineers, 1987). Fetter (1994) provides a list of capillary-fringe lengths for selected soil types. For the purpose of this manual, the USACE definitions for wetland and wetland hydrologic characteristics are used because they provide a quantitative basis for wetland definition.

Wetlands are considered to be waters of the State and activities within these areas are regulated by the Freshwater Wetlands Protection Act Rules N.J.A.C. 7:7A (New Jersey Department of Environmental Protection, 2003). On March 12, 1994, the NJDEP assumed responsibility for administering the Federal Wetlands program (also known as the "Federal 404 program") in **delegable waters** as defined in N.J.A.C. 7:7A-1.4. In **non-delegable waters**, the USACE retains jurisdiction under Federal law, and both Federal and State requirements apply. A wetland mitigation project in non-delegable waters requires two permits--one from the NJDEP under N.J.A.C. 7:7A-2.1, and one from the USACE under the Federal 404 program.

Growing Season

In general, the growing season refers to the time period during which plant growth takes place, and is typically limited by climatic factors including temperature (in temperate regions), water availability (in dry regions), and length of daylight (in the Arctic). The Natural Resources Conservation Service (NRCS) defines the growing season as the portion of the year during which soil temperatures at 50 cm (19.7 in.) below the soil surface are above 5 °C (41 °F) (Natural Resources Conservation Service, 1995). This definition of the growing season is used by the USACE and has application in regions such as the northeastern United States, where seasonal temperature changes limit the growing season. Using the NRCS definition, the growing season can be approximated as the period of time between the average dates of the last killing frost in the spring and the first killing frost in the fall (Natural Resources Conservation Service, 1995).

New Jersey can be divided into five distinct climate regions. The Northern Climate Zone, which encompasses about one-quarter of New Jersey, generally supports the shortest growing season in the State, approximately 155 days per year. Within this climate zone, the average dates of the last killing frost in the spring and the first killing frost in the fall are May 4 and October 7, respectively; however, these dates vary widely within the region as well as from year to year (Office of the New Jersey State Climatologist, 2007). In contrast, the Southwest Climate Zone is marked by the longest growing season in the State, with the last spring killing frost occurring about 4 weeks earlier, and the first fall killing frost occurring about 4 weeks later than in the North. Therefore, the growing season is 2 months longer in the South than in the North. For more information on New Jersey's climate zones, visit the Office of the New Jersey State Climatologist website at http://climate.rutgers.edu/stateclim/?section=uscp&target=NJCoverview .

The growing season for a wetland in New Jersey can be approximated at a finer scale by using the NRCS's Wetlands Climate (WETS) Table, which can be accessed at http://www.wcc.nrcs.usda.gov/cgibin/getwetst.pl?state=New+Jersey. The WETS Table uses data from the National Weather Service (NWS) Cooperative Network to calculate the normal range of growing-season dates for a geographic area over a given period of time. Stations in

New Jersey for which growing-season dates were calculated are shown in Figure 1, and corresponding information for each site is shown in Table 1. A detailed explanation of the WETS Table program and the methods used to calculate growing season are available at http://www.wcc.nrcs.usda.gov/climate/wets_doc.html.

Wetland Hydrologic Characteristics

Hydrologic characteristics are often cited as the most important variables in the creation, restoration, and maintenance of wetlands (Mitsch and Gosselink, 2000; Tiner, 2005). Hydrology is the science or study of water and its properties, movement, and distribution throughout the Earth. The hydrologic cycle refers to the constant movement of water among the land, surface and subsurface bodies of water, and the atmosphere (Tiner, 2005). Precipitation, evapotranspiration, ground-water flow, and surface-water flow are the major components of the hydrologic cycle (Carter, 1996). Each of the individual components varies in magnitude from wetland to wetland, such that no two wetlands exhibit identical hydrologic characteristics. Hydrologic characteristics not only vary among wetlands, but they also can vary annually, seasonally, and daily within a given wetland (Tiner, 2005).

Hydroperiod refers to the pattern of water-level fluctuations that take place in a wetland over time. The depth, duration, and frequency of fluctuations all factor into a wetland's hydroperiod, and these fluctuations may exhibit short-term, seasonal, or interannual patterns (Tiner, 2005). The seasonal hydroperiod in particular has been likened to a hydrologic signature for each wetland type, because the pattern remains relatively constant from year to year (Mitsch and Gosselink, 2000). For example, in New Jersey as in much of the northeastern United States, water levels tend to rise during the spring as a result of wetter conditions. This pattern is reflected in Figure 2, which is a **hydrograph** that shows the hydroperiod for a forested wetland located in New Jersey's Pinelands area based on ground-water levels measured continuously during 2005. In addition to seasonal variations, hydroperiods undergo interannual fluctuations, most notably as the climate cycles among wet and dry years. The hydroperiod is a critical determinant of a wetland's structure and function as it directly influences important wetland attributes such as biotic composition, primary productivity, and nutrient cycling (Mitsch and Gosselink, 2000).

Physiographic Regions in New Jersey

New Jersey can be divided into four major physiographic provinces (Figure 3), each of which is characterized by unique geologic and hydrologic properties. A geologic division formed by the **Fall Line** separates the State into northern and southern parts. The Fall Line roughly parallels U.S. Route 1 from Trenton to New York City and is marked by a series of waterfalls along river courses (Watt, 2000). The Valley and Ridge, New England (also called the Highlands), and Piedmont Physiographic Provinces lie north of the Fall Line. These provinces are underlain by older, resistant, consolidated rocks. South of the Fall Line is the Coastal Plain Physiographic Province. In contrast to the northern physiographic provinces, the Coastal Plain Physiographic Province is underlain by younger, weaker, unconsolidated sediments (Watt, 2000).

Because hydrologic characteristics are defined in large part by geologic properties, contrasting geologic characteristics found north and south of the Fall Line are reflected in both ground-water and surface-water hydrologic characteristics. The topography of the land surface, the nature and extent of the hydrogeologic layers through which ground water moves, and the quantity of precipitation that percolates through the soil to recharge the ground-water system are important defining characteristics of wetland-supporting landscapes. North of the Fall Line, aquifers and confining units are composed of Pleistocene glacial and stream deposits, fractured shale, limestone, sandstone, conglomerate, and crystalline-rock units; south of the Fall Line, they consist of unconsolidated gravels, sands, and clays. These variations in the underlying geologic properties exert considerable control over ground-water movement because hydrologic characteristics are defined in large part by geologic properties such as grain size, sorting, resistance to erosion, and fracturing (Watt, 2000). Stream characteristics also are shaped by the underlying geologic properties. Streams located north of the Fall Line tend to have steep gradients with rocky bottom material, whereas those located south of the Fall Line in the Coastal Plain Physiographic Province have gentler slopes and sandier streambeds (Watt, 2000). In addition, streamflow in the Coastal Plain consists predominantly of ground-water **discharge** and therefore is less responsive to variations in rainfall than streams north of the Fall Line (U.S. Geological Survey, 1986).

During the Pleistocene Epoch, New Jersey experienced at least three glaciation events. The last glacier—from the late Wisconsinan advance—covered large portions of the northern physiographic provinces in New Jersey. As this glacier retreated about 20,000 years ago, it left behind deposits of stratified drift (well-sorted and layered material deposited by glacial meltwater) and till (an unsorted mixture of clay, silt, sand, gravel, and boulders deposited directly from the glacial ice) north of the limit of glaciation. Stratified sands and gravels were deposited in the valleys and lowlands, whereas silts and clays settled in glacial lakes (Witte, 1998). The sand and gravel deposits, which reach up to 350 ft thick, can be highly productive **aquifers**. Till was deposited in ridges and upland areas, where it is typically 30 to 40 ft thick. South of the extent of the Wisconsinan glaciation, till is found in discontinuous patches in upland areas—remnants of previous glaciations (U.S. Geological Survey, 1985).

The geologic differences between the northern and southern portions of the State are evident in the types of wetlands that predominate in the two regions. In the northern part of the State, glacial lakes and depressions formed at the end of the Wisconsinan glaciation have been succeeded by predominantly **palustrine** freshwater wetlands. Over time, as the glacial lakes fill with organic matter, they become emergent, scrub-shrub and/or forested wetlands. Precipitation and ground-water discharge from glacial sediments and fractured crystalline rock are the main sources of water for these wetlands (U.S. Geological Survey, 1996). In some places where the deeper underlying sediments are confined by glacially deposited silts and clays, freshwater wetlands (including the Great Swamp) have formed (Vecchioli and others, 1962). Freshwater wetlands such as the Great Swamp act as regional discharge areas for deeper ground-water flow (Vecchioli and others, 1962).

About 87 percent of New Jersey's total wetland area lies south of the Fall Line in the Coastal Plain. This area includes about 95 percent of the State's **estuarine** wetlands and 75 percent of its marshes and swamps (Tiner, 1985). In the Outer Coastal Plain, wetlands tend to form along rivers and streams (ground-water fed) and in low-lying coastal areas. Much of the forested wetlands of the New Jersey Pinelands are associated with rivers and streams. In the Inner Coastal Plain, wetlands develop where clays and silts form impermeable layers that impede the downward movement of water (U.S. Geological Survey, 1996).

Valley and Ridge

The Valley and Ridge Physiographic Province occupies the northwestern corner of the State (Figure 3) and is characterized by long, parallel, northeast-southwest-trending ridges and valleys. Variation in resistance to erosion among the underlying rock formations, in combination with historical folding and thrusting, is responsible for the pattern of alternating ridges and valleys. In general, ridges in this area are underlain by erosion-resistant layers of conglomerate, sandstone, or dolomite, whereas valleys are underlain by more easily erodible layers of siltstone, shale, limestone, or dolomite (Swain and others, 1991). The **permeability** of sandstones and shales is variable depending on the amount of weathering and fracturing they have undergone (Watt, 2000). Carbonate rocks (limestone, dolomite) can be highly permeable and form highly productive aquifers (Swain and others, 1991).

New England (Highlands)

The New England Physiographic Province lies southeast of the Valley and Ridge Province and is dominated by a high, mountainous plateau (Figure 3). The New England Province is underlain predominantly by metamorphic crystalline rocks—namely, granite, gneiss, and small amounts of marble. These rocks are the oldest in New Jersey and were formed by the melting, recrystallization, and subsequent deformation of sedimentary rocks deposited in the region. Northeast-southwest-trending hills and valleys are found within the landscape as well, with rock composition similar to that of the Valley and Ridge Province. The metamorphic crystalline rocks of the New England Province generally have low permeability and are unproductive aquifers except where they are weathered and fractured. The more highly permeable and productive aquifers of this province include glacial deposits and valleys underlain by carbonate rocks (Watt, 2000). Ground-water flow systems in the region are local (short distance from recharge area to discharge area); there is no significant regional ground-water flow system (Carswell and Rooney, 1976).

Piedmont

The Piedmont Physiographic Province is separated from the New England Physiographic Province by a series of major faults. From the highlands of the New England Province, the Piedmont lowlands slope gradually to the Coastal Plain and are interrupted by basalt ridges, including the Watchung Mountains (Wolfe, 1977). In general, the Piedmont is characterized by interbedded sandstone, shale, conglomerate, basalt, and diabase. Shale and sandstone underlie the valleys and lowlands; basalt and diabase, which are more resistant to erosion, form the ridges and uplands. Water is found in the joints and fractures of the shales and sandstones such that they are, in places, capable of yielding large quantities of water. The basalt and diabase generally have low permeability and are poor aquifers.

The extensive freshwater wetland areas of the New Jersey Meadowlands lie in the broad lowland region between the Watchung Mountains and the Palisades Ridge. Here, layers of organic peat or organic muck soils up to 30 ft thick have accumulated above impermeable beds of glacially deposited silt and clay (Wolfe, 1977). The wetlands of the Great Swamp National Wildlife Refuge exhibit similar geohydrologic features in that organic muck deposits of variable thickness overlie impermeable beds of clay and silt which, in turn, confine the underlying sand and gravel aquifer. In the case of the Great Swamp, the recharge area for the underlying sand and gravel aquifer is at a higher elevation than the surface of the swamp. Consequently, the **hydraulic head** is higher than land surface in these areas, which causes water from the aquifer to flow upward through the confining unit into the swamp (Turner and others, 1993). Water is then lost through evapotranspiration or surface-water outflow.

Coastal Plain

New Jersey's Coastal Plain Physiographic Province exhibits topographic, geologic, and hydrologic characteristics that are markedly different from those of the three northern provinces. Unlike regions north of the Fall Line, the topography of the Coastal Plain is generally flat to very gently undulating. The Coastal Plain is underlain by a seaward-thickening wedge composed of alternating layers of unconsolidated clay, silt, sand, and gravel (Vowinkel and Foster, 1981; Watt, 2000). These sediments begin as a featheredge along the Fall Line and thicken southeastward, reaching a thickness of more than 6,500 ft in southern Cape May County (Zapecza, 1989). Layers composed mainly of silts and clays make up the confining units, whereas layers of sand and gravel form the aquifers through which ground water moves (Watt, 2000).

Inner Coastal Plain

The Inner Coastal Plain tends to be higher in altitude and has formations of greater topographic relief than the Outer Coastal Plain (Newell and others, 2000). The Inner Coastal Plain's surficial aquifer system is characterized by the outcrop of deeper **confined aquifers** where they are unconfined (Buxton, 1995). The surficial deposits of the Inner Coastal Plain are older than those of the Outer Coastal Plain (Newell and others, 2000). In the Inner Coastal Plain, wetlands develop primarily where clays and silts form **confining layers** that impede the downward movement of water (U.S. Geological Survey, 1996). In these areas, precipitation (either direct or as surface runoff), overbank flooding, and shallow seasonal ground water are the main sources of hydrologic input.

Outer Coastal Plain

The Outer Coastal Plain is a region of low altitude and is characterized by formations of low topographic relief (Newell and others, 2000). The Kirkwood-Cohansey aquifer system is an extensive sand and gravel aquifer system that underlies 3,000 mi^2 of the Outer Coastal Plain (Buxton, 1995) and supports extensive wetland areas. Because it is both shallow and unconfined, streams, wetlands, and other surface-water bodies generally have a strong hydraulic connection with the Kirkwood-Cohansey aquifer system (Watt, 2000). Because the Outer Coastal Plain is made up of predominantly sandy soils through which water infiltrates very quickly, ground water is the primary water source for wetlands in this sub-province. For example, white cedar swamps, prevalent in the Pinelands area, are recurrently wet from ground-water discharge (Newell and others, 2000). Surface-water input from precipitation plays a very small role unless a confining layer is present.

Wetland Types and their Hydrologic Functions

A number of classification schemes have been created to categorize wetland types (Novitzki, 1979; Cowardin and others, 1979; Breden, 1989; Brinson, 1993). These classification systems rely on a variety of parameters, ranging from vegetation type to water depth and degree of flooding to functionality, to categorize wetlands. For the purpose of this manual, the Hydrogeomorphic Approach for Assessing Wetland Functions (HGM Approach) developed by the USACE is used (Brinson, 1993). The HGM Approach is advantageous because it focuses on hydrologic differences between wetlands and, unlike many other classification schemes (such as Cowardin and others (1979) and Breden (1989), distinguishes wetland features that are independent of the distribution of plant communities.

In a study of forested wetlands in northeastern New Jersey, Ehrenfeld and others (2003) suggest that the usefulness of the HGM classification in urban and suburban wetlands is limited because in general, hydrologic conditions in urban and suburban wetlands may be altered as a result of disturbances brought on by urbanization. For example, urban and suburban wetlands are more likely to show "flashy" changes in water levels (marked by frequent, rapid, large rises and declines), and they tend to have a lower frequency of saturated conditions than wetlands found in non-urban environments. The authors concluded that HGM classifications for urban wetlands in northern New Jersey, and likely urban wetlands in general, are limited by the variability of the sources of disturbance from current and historical land uses (Ehrenfeld and others, 2003). Because much of New Jersey is urban or suburban, wetland designers may need to rely on a different classification scheme to characterize the movement of water through a mitigation site that is situated in this type of landscape. One possibility is the system of Novitzki (1979) as used by Pierce (1993), which offers an alternative hydrogeomorphic classification of wetlands based on topographic position and ground-water/surface-water interaction.

Despite these limitations of the HGM Approach, it is most appropriate classification scheme for understanding hydrological parameters for the purpose of designing a water budget. The classification used in the HGM Approach is composed of three core components: geomorphic setting, water source and transport, and **hydrodynamics**. Most wetlands in New Jersey are a unique combination of these three factors, each of which contributes to the overall wetland water budget. In addition to classification, two other key principles of the HGM Approach are (1) the use of **reference wetlands** to establish and assess a range of wetland functions, and (2) the collection of scientific data to assess wetland function. A brief synopsis of the three hydrogeomorphic components is provided below; for complete details on the HGM classification system, see Brinson (1993).

Geomorphic Setting

Geomorphic setting is the topographic location of a wetland in the surrounding landscape, otherwise referred to as "landscape position." The HGM Approach separates wetlands into four geomorphic settings--depressional, extensive peatlands, riverine, and fringe--based on a distinctive combination of hydroperiod (cyclical pattern of water-level fluctuations), dominant direction of water flow, and zonation of vegetation (Brinson, 1993). Many wetland communities in New Jersey can be characterized by some combination of the geomorphic settings described in the HGM Approach.

Depressional Wetlands

Depressional wetlands typically receive most moisture from precipitation, directly or as surface runoff (Mitsch and Gosselink, 2000). Depressional wetlands also may receive substantial amounts of water from ground-water discharge. In the Highlands and Piedmont Provinces, depressional wetlands are most commonly found at low elevations between the ridges, where clay deposits both trap precipitation and prevent ground water from rising to the surface. In the Outer Coastal Plain, most depressional wetlands are ground-water-fed as a result of the high permeability of the sandy soils present. Depressional wetlands of the Inner Coastal Plain receive water from several sources, including precipitation, overbank flooding, and shallow ground water.

Extensive Peatlands

Extensive peatlands extend over large tracts of land such that the peat substrate dominates the movement and storage of water and isolates the wetland from its mineral substrate. Surface patterns develop that are independent of underlying topography (Brinson, 1993). The Great Swamp is an example of extensive peatlands in New Jersey.

Riverine Wetlands

Riverine wetlands form as linear strips along rivers and streams. Surface flow in these wetlands is predominantly unidirectional (Brinson, 1993). In New Jersey, water-level fluctuations in riverine wetlands range from short and flashy in urban and suburban streams to long and steady in undeveloped, higher order streams.

Fringe Wetlands

Fringe wetlands are estuarine and **lacustrine** wetlands that exhibit predominantly bidirectional surface flow resulting from the movement of water into and out of the wetland system by wind and waves. Water-level changes in these wetlands are relatively long and steady. Examples of fringe wetlands include estuarine and freshwater-tidal wetlands and wetlands along the edges of lakes that are subject to wind and waves.

Ground-Water Slope Wetlands

Although ground-water slope wetlands are categorized as depressional wetlands in the HGM Approach, other wetland classification schemes (such as that of Novitzki (1979)) distinguish between depressional and ground-water slope wetlands. For the purpose of this manual, ground-water slope wetlands (also known as seep wetlands) represent a fifth category of wetlands commonly found in New Jersey. These wetlands occur along slopes where the **water**

table intersects the land surface. Ground-water discharge at such seepage faces and breaks in slope is a steady source of water to the wetland system. Surface-water inflow and precipitation also may contribute to the water budget of ground-water slope wetlands (Pierce, 1993).

Water Source and Transport

In the HGM Approach, hydrologic inputs to wetlands are simplified to three main sources of water--precipitation, surface or near-surface flow, and ground-water discharge. A detailed water budget indicates the quantity of water that each source contributes to the hydroperiod. The relative contribution of each water source to some of the major wetland types described by Brinson (1993) is shown in Figure 4.

Precipitation

Precipitation is a source of water for nearly all wetlands, but its importance varies depending on the relative contributions of other water sources. Where precipitation is the dominant water source, water levels may be variable because evapotranspiration can cause substantial drawdown. Depressional wetlands and wetlands that rely on **perched ground-water** tables, such as **ombrotrophic** bogs and wet mineral flats, are examples of precipitation-driven wetland systems.

Surface or Near-Surface Flow

Surface or near-surface inflow to a wetland can occur as **channelized** streamflow, overbank flooding, or overland flow (**non-channelized flow**). Examples of wetlands dominated by surface-water inflow include riverine wetlands, fringe wetlands, peatlands, **alluvial swamps**, and tidal wetlands (Mitsch and Gosselink, 2000).

Ground Water

Wetlands dominated by ground-water discharge receive much of their water from regional or perched ground-water systems. Fens (a peatland that is fed by ground water), ground-water depressional, and ground-water slope wetlands represent types of wetlands typically dominated by ground-water discharge.

Hydrodynamics

As described in the HGM classification system, hydrodynamics refers to the motion of water and its capacity to do work. For example, the capacity of water to transport sediments and nutrients is influenced by the direction and strength of water movement. In the HGM classification system, there are three main categories of hydrodynamic properties—vertical fluctuation of the water table, unidirectional flow, and bidirectional flow.

Vertical Fluctuations

Vertical fluctuations of the water table result mainly from changes in rates of evapotranspiration, ground-water withdrawals, ground-water discharge, and infiltration from precipitation. Fluctuations of the water table range from seasonal fluctuations within multiyear cycles to a relatively steady water table with little fluctuation (Brinson, 1993). Examples of wetlands in which water levels undergo vertical fluctuations are depressional wetlands and glacial bogs.

Unidirectional Horizontal Flow

In wetland systems dominated by unidirectional surface or near-surface flow, the flow velocity generally corresponds to the gradient (Mitsch and Gosselink, 2000), except in a flashy urban system. Unidirectional flow can range in magnitude from slight surface movement to strong bottom currents (Brinson, 1993). Riverine wetlands typically exhibit unidirectional flow.

Bidirectional Flow

Bidirectional flow occurs in wetlands dominated by tidal and wind-generated water-level fluctuations (Mitsch and Gosselink, 2000). Fringe wetlands such as tidal freshwater wetlands and palustrine freshwater wetlands adjacent to lakes commonly demonstrate bidirectional flow.

Mitigation Site Selection

One of the most critical steps in the mitigation process is site selection. The mitigation site must be able to support a wetland ecosystem—one that is both long-term and self-sustaining. Factors that must be considered when selecting a site include mitigation goals, landscape position, wetland function, and surrounding land use.

Wetland site selection should be mitigation-goal driven, particularly in terms of wetland type and function. For example, if one of the mitigation objectives is to create a forested wetland, then the landscape should be well-suited to the support of this type of wetland. Once mitigation objectives have been defined, the likelihood of success of a mitigation project can be maximized by enhancing, creating, or restoring wetlands in the most appropriate locations by considering such landscape characteristics as **hydrogeomorphology**, habitat connectivity, and historical land uses. An understanding of the relation between location and past occurrence of wetlands is helpful; if wetlands historically were present in a given area, the landscape is likely to be able to support a wetland environment again. Historical topographic maps can be used to locate former wetland areas. An additional resource that is useful when selecting an appropriate wetland mitigation site is the Natural Resource and Conservation Service's Web Soil Survey (WSS), which can be accessed at http://websoilsurvey.nrcs.usda.gov/app/.

It also is important to consider the functional goals for the proposed wetland—for example, water storage, water-quality protection, nutrient cycling, plant diversity, and/or wildlife habitat—as well as surrounding land use, including recent or proposed development. For example, new development may cause an increase in channelized (rather than overland) flow, which could affect the water budget.

Reference Sites

Another way to increase the likelihood of success of a wetland mitigation project is to identify "reference wetlands" adjacent to or near the mitigation site. Brinson and Rheinhardt (1996) define reference wetlands as "sites within a specific geographic region that are chosen, for the purposes of functional assessment, to encompass the known variation of a group or class of wetlands, including both natural and disturbance-mediated variations." Reference sites indicate the types of wetlands that the landscape can support as well as how they function. Reference sites should be located where data have been or can be collected, and where wetland indicators have been related to ecosystem functions (Brinson, 1993). Reference sites should also be of similar hydrogeomorphic function, hydroperiod, and have similar vegetative characteristics and structure as the system that is intended to be created. Comparison of data collected at a proposed mitigation location to information collected at a reference site can provide insight into the hydrologic properties of the mitigation site, including source of water, water level, and flow pattern. Reference-site data can be used to establish relations among hydrologic inputs and outputs for a mitigation site and, in turn, to document expected hydrologic characteristics.

Geographic Information System (GIS) Assessment for Mitigation Site Selection

An initial GIS analysis of available geographic information is recommended to assist wetland designers in determining the most appropriate location for the proposed mitigation site(s); this analysis also should be used to assist in the identification of reference sites. The process of analyzing this information will be different for each proposed mitigation project, depending on the goals. The NJDEP Bureau of Geographic Information Systems (BGIS) provides GIS coverages for New Jersey. These coverages include a range of types of information (listed below) and are available for download at http://www.state.nj.us/dep/gis/. The BGIS web site also provides links to other sources of available digital spatial information, such as the New Jersey Geological Survey, Delaware River Basin Commission, New Jersey Department of Transportation, and New Jersey Pinelands Commission. Links to these and other data sources are found at http://www.nj.gov/dep/gis/othersources.html.

The following is a list of BGIS coverages that may be useful in identifying potential wetland mitigation sites:

1. Wetland mapping (not National Wetlands Inventory)
2. Hydrography mapping
3. Open space mapping (Federal, State, local)
4. Bedrock geology
5. Geologic folds—North and Central
6. Digital elevation hillshade grid (DEM)
7. Dams
8. Climate stations
9. Historical sites

10. National heritage priority mapping
11. Wellhead protection areas
12. New Jersey Pollutant Discharge Elimination System (NJPDES) surface-water and ground-water discharge points
13. Surface-water intakes
14. Public community water-supply wells
15. Landscape project data—Federal and State endangered and threatened species habitat mapping, including species of special concern:
    - Bald eagle foraging
    - Wood turtle
    - Urban peregrine falcon
    - Critical wetland forest
    - Critical forest
    - Critical grassland
    - Critical emergent wetland
    - Critical beach-dune
18. Ambient stream-quality monitoring sites
19. Ambient Biomonitoring Network (AMNET) sites—streams
20. Surface-water-quality standards/Category One waters
21. Soil Survey Geographic (SSURGO) database.

In New Jersey, properties where hazardous contamination may exist cannot be used for wetland mitigation, unless the property is remediated and receives a letter of "No Further

Action" from the NJDEP Site Remediation Program. For this reason, the following coverages are helpful in conducting a site-selection search:

1. Known contaminated sites
2. Toxic release inventory
3. Chromate waste sites
4. Ground-water contamination areas
5. Solid-waste landfills.

The GIS assessment allows the user to evaluate relatively large land areas efficiently, and can provide additional data that may contribute to other goals of the mitigation project. Once the potentially suitable mitigation properties have been identified, the next step is to contact the property owner. Once the property owner has granted access to the property, an investigation should be conducted on-site. Individuals with expertise in wetlands creation, restoration, or enhancement should be retained to investigate the property, determine its hydrologic characteristics, and design and implement the project.

Case Studies

It is critical that wetland designers understand all of the potential factors that affect the movement of water through the prospective mitigation site and how those factors can be altered so that water moves through the site in such a way that the desired wetland condition is created. For example, if ground water is the dominant source of water at the site, the wetland designer needs to examine how the soils and other underlying geologic features affect the movement of ground water throughout the site. Is the ground water going to be able to move vertically within the existing soil profile to create the desired wetland condition, or are the soils too compact to allow for sufficient vertical movement? Or is there a clay soil lens present in some portion of the site that serves to hold water at the surface such that surface water, overland flow, and/or direct precipitation are the main source(s) of water in a portion of the site? Three examples of situations in which the hydrogeologic and soil properties of the proposed mitigation site were poorly understood are discussed below.

Case Study A

A recent cranberry bog restoration project that was undertaken in the Pinelands area of the Outer Coastal Plain demonstrated how soil compaction can dramatically affect the movement of water through a site, even in the sandy soils that characterize this physiographic province. Cranberry bogs were created by a network of on-stream dams and ditches such that both surface- and ground-water levels could be controlled for the production of cranberries. Initially, it appeared that if the network of ditches and dams was disabled, the bogs, which were wetlands prior to conversion for cranberry production, would become wetlands again. Although the disabling of dams and ditches was an integral part of reestablishing the site's former hydrologic characteristics, it was discovered during an on-site investigation that the soils were too compact to allow for the vertical movement of ground water to the surface of the bogs. Without this key input of water, the bogs would not become wet again as anticipated. The soils within the bogs had to be loosened to allow ground water to move upward into the system. When the soil was broken up, ground water almost immediately moved toward the surface, thus restoring the main source of water to the wetland.

Case Study B

Wetland designers sometimes erroneously rely solely on the results of the water-budget analysis without understanding how the hydrogeologic and soil properties of the site may affect some of the assumptions used in the water-budget analysis. For example, a wetland designer working at a site in a valley in the New England Physiographic Province determined that the site's drainage area was sufficiently large that a precipitation-driven wetland could be created. A water budget developed for the site indicated that rainfall in the drainage area would be sufficient to create a precipitation-driven wetland. However, the effects of the underlying geology on the site's hydrologic characteristics were inadequately considered. Analysis of data collected on-site would have shown the presence of a shallow water table in the carbonate rock (porous limestone) beneath the site, which was overlain by a thin layer of highly organic soil; and that, ground-water discharge was the actual dominant source of water at the site. Because the design failed to account for this additional source of water, a pond was created at the site rather than the proposed wetland type.

Case Study C

The importance of landscape position and adequate on-site investigation was demonstrated when a wetland designer was charged with creating a wetland in the Piedmont Physiographic Province. The design was developed based on the assumption that decreasing the elevation of the site to that of nearby wetlands would cause a ground-water-driven wetland to be created. The design required an excavation of 5 feet or more to reach ground water; however, when the design was implemented, bedrock was encountered within a few feet of the surface. As a result, the proposed mitigation project failed. If landscape position, geologic characteristics, and soils at the site had been appropriately investigated, the project would not have been attempted at this site. (For a detailed summary of the relation between landscape position and geologic characteristics at potential wetland mitigation sites, refer to Kentula and others (1992).)

Additional Points

As mentioned in the previous example, one of the most common problems that wetland designers encounter is that they are prevented from selecting the most suitable site on which to create wetlands. Many times, in an effort to save money, permittees hire wetland designers to create a wetland, but do not allow the designer the freedom to choose the most appropriate site. Instead, designers are often required to "make it work" on a piece of real estate that the permittee already owns. This often results in a higher than anticipated cost for the permittee because if the mitigation project partially or completely fails, the permittee is then required to perform additional mitigation at another location. Selecting the most appropriate location is not only critical to successfully creating a wetland but it can also be less costly for the permittee in the long run.

One of the other most common problems that wetland designers encounter is that the permittee's proposed project schedule is often very short. Time constraints may prevent the wetland designer from performing the necessary on-site investigations to determine if a site is suitable for wetland mitigation. By failing to identify the critical nature of collecting data on-site, the permittee risks constructing a partially or completely unsuccessful mitigation project, which again results in increased costs as well as potential delays to the permitted project since mitigation must be completed prior to or concurrent with the permitted project.

Summary

Every wetland mitigation site exhibits unique hydrologic and geologic characteristics that affect the movement of water through the site. Selection of an appropriate site coupled with the development of a site-specific water budget is the foundation for a successful mitigation project. The mitigation site should have a high probability of supporting a long-term and self-sustaining wetland ecosystem. An appropriate site is one that is located within an area where a wetland formerly existed or where the hydrologic conditions favor a wetland environment and that has the potential to meet the goals of mitigation with respect to wetland type and function. A site's geographic setting (physiographic province, north or south of the line of glaciation), its position in the landscape (in a depression, on a slope, alongside a river), and the surrounding land use provide clues regarding its primary geologic and hydrologic influences that aid in site selection. Once a suitable site has been selected, the next step is to develop a reasonably representative site-specific water budget. During this stage, a detailed analysis of the selected site and the likelihood that it will achieve the desired mitigation goals is conducted.

PART II: Developing a Water Budget

As shown in Part I, geographic location, wetland type, and a site-selection investigation can provide information about the hydrologic influences on a wetland mitigation site. This information can be used to develop a site-specific water budget, which in turn can be used to assess hydrologic influences in more detail. Part II describes the data sources and methods that can be used to develop a water budget for a wetland mitigation site that is useful and illustrative of a range of conditions. This section also touches on some of the sources of error and uncertainty in developing a reasonably representative water budget and related considerations that should be taken into account when conducting a sensitivity analysis. An in-depth example of a water budget for a hypothetical mitigation site in New Jersey is presented in Appendix 2.

Water Budget

The hydrologic cycle of a wetland, or the movement of water within the wetland system, can be expressed in a water budget, an equation that accounts for water inflows to and outflows from the system:

$$\Delta S = [P + S_i + G_i] - [ET + S_o + G_o]$$

where

ΔS = change in volume of water storage in a defined area over time

P = precipitation

S_i = surface-water inflow

G_i = ground-water inflow

ET = evapotranspiration

S_o = surface-water outflow

G_o = ground-water outflow.

This equation represents the ideal case, when there is no uncertainty in the measurement of any of the water-budget components. In practice, determination of the water budget involves uncertainty such that:

$$[P + S_i + G_i] - [ET + S_o + G_o] = \Delta S + \text{uncertainty}.$$

Each of the terms of the water budget can be expressed as depth per unit time (cm/mo, in/mo) or as volume per unit time (m^3/mo, ft^3/mo) (Mitsch and Gosselink, 2000). For the purpose of this manual, water budgets are expressed in equivalent depths per month rather than volumes per month.

The components of the wetland water budget are shown in Figure 5. As expressed in the equation, the water budget is used to evaluate the change in volume of water stored in a wetland over time (Tiner, 2005). Precipitation, surface-water inflow, and ground-water inflow represent sources of water, or inputs, whereas evapotranspiration, surface-water outflow, and ground-water outflow represent water losses, or outputs (Tiner, 2005). By assessing the relative magnitude and variability of individual components, a water budget serves as a valuable tool in understanding the hydrologic processes that take place in a wetland, and provides insight into the potential effects of future changes to the hydrologic characteristics of the system (Carter, 1996). It is important that there be a sufficient amount of water available during the growing season to develop conditions that support the development of **hydrophytic vegetation**. Additional reasons for developing and evaluating site-specific water budgets are (1) to determine the pattern of the hydroperiod under varying conditions in the future, (2) to determine how to change the hydroperiod by changing the parameters of the water budget, (3) to determine whether the proposed functions can be supported by the hydroperiod, (4) to determine whether the proposed hydrogeomorphic classification and the site are appropriate for the construction of the proposed wetland, and (5) to judge the feasibility of the site (G. Pierce, Froghome Environmental, written commun., 2008).

Precipitation is water that falls from the atmosphere in any form—rain, snow, sleet, hail, or fog. Precipitation is a source of water for all wetlands. Precipitation can fall directly on a wetland or it can be transported into a wetland from surrounding areas by way of surface- or ground-water inflow (Carter, 1996). However, for the purpose of estimating a hydrologic budget, only the direct input of precipitation is quantified. In general, precipitation varies with climate and many regions have distinct wet and dry seasons (Mitsch and Gosselink, 2000).

Surface-water inflow to a wetland is derived from channelized streamflow, non-channelized flow, and seasonal or periodic flooding of lakes, ponds, and rivers. Surface-water outflow results from water draining off the land surface, typically into streams and rivers (Tiner, 2005). Surface-water inflows and outflows vary seasonally and generally correspond to variations in precipitation and spring thaw. For example, surface-water outflow from wetlands that rely on precipitation as their main source of water supply is commonly highest during the wet season and during periods of flooding (Carter, 1996); however, in wetlands for which ground water is a major contributor, surface-water outflow tends to be more evenly distributed throughout the year. Depending on the temporal balance of inflows and outflows, surface water may be present in a wetland on a permanent, seasonal, or temporary basis (Carter, 1996).

Evapotranspiration is the combination of water lost to the atmosphere through vaporization from soil or surfaces of water bodies (evaporation) and water that passes through plants to the atmosphere (transpiration) (Mitsch and Gosselink, 2000). The rate of evapotranspiration in a wetland is affected by several meteorological, physical, and biological variables including solar radiation, surface temperature, wind speed, relative humidity, available soil moisture, and vegetation type and density (Carter, 1996). Evapotranspiration varies both seasonally and daily. The evapotranspiration rate is higher during seasons when plants are actively growing and transpiring than during seasons when they are dormant (Carter, 1996), and tends to be lower at night and on cool, cloudy days and higher during the day and on hot, sunny days.

Wetlands may receive ground-water inflow, recharge ground water (outflow), or both (Winter and others, 1998). Ground-water inflow represents water that is discharged to the land surface (or a 0-18-in.-deep zone) from underlying sediments. This discharge may occur in places where the wetland's water level is lower than the adjacent water table, or in areas of steep slopes where the water table intersects the land surface at seepage faces and at breaks in slope. Many natural wetlands in the Northeast are ground-water discharge sites (Tiner, 2005). Ground-water outflow occurs when the wetland's water level is higher than the adjacent water table. In this case, ground water flows out of the wetland and moves downward through the soil and may replenish or recharge nearby ground-water supplies.

Storage in a wetland consists of surface water, soil moisture, and ground water. The storage capacity of a wetland refers to the space available to store such water (Carter, 1996). If the wetland's water level is below land surface, the storage capacity includes the unsaturated zone and the difference between the lowest point in the wetland basin and the elevation at which water from the wetland will spill over land. In general, the higher the water table, the lower the storage capacity of a wetland. For many wetlands, storage capacity varies seasonally with water-table fluctuations; during the growing season, as evapotranspiration increases and the water table falls, storage capacity typically increases (Carter, 1996). As the water-budget equation indicates, the change in storage in a wetland represents the balance between water inflow to the wetland and water outflow from the wetland. During a precipitation event, when storage capacity is high, ground-water outflow, G_o (in the form of **infiltration**), may be a large component of a wetland's water budget; when storage capacity is low, surface-water outflow, S_o (in the form of runoff), is likely to be an important component.

The method for preparing and presenting water budgets and hydroperiods described in this manual is derived from Pierce (1993).

If the proposed mitigation site is adjacent to a freshwater river or stream influenced by tides, the water-budget equation should be adjusted as follows:

$\Delta S = [P + S_i + G_i + T_i] - [ET + S_o + G_o + T_o]$

where:

T_i = tidal inflow

T_o = tidal outflow

Although tides provide a predictable water input, accurate calculation of this input is still important in determining the amount and frequency of this water supply. Some sources of tide data for New Jersey are NOAA's Tides and Currents web page http://tidesandcurrents.noaa.gov/station_retrieve.shtml?type=Tide%20Data&state=New+Jersey&id1=853 and the USGS Tide Gage Network http://pubs.usgs.gov/fs/2007/3064/pdf/fs2007-3064.pdf. Tide gages should be placed on site if data cannot be obtained from available sources.

Water-Budget Requirements

As part of the approval process for a proposed freshwater wetland mitigation site, the NJDEP requires that an anticipated water budget be submitted. The water budget for a proposed wetland mitigation site must be calculated using daily values of each water-budget component because wetlands are defined by the number of days of saturation during the growing season. Daily values must be obtained, measured, or estimated for each component of the water budget to show a complete understanding of the anticipated wetland hydroperiod throughout the year. Because historic data do not necessarily predicted future conditions, water budgets can only approximate future patterns (G. Pierce, Froghome Environmental, written commun, 2008).

Daily-value data should be selected to represent a wet year, a dry year, and an "average" year (meaning representative of normal or typical conditions) to account for the variability associated with wet and dry conditions. The selection of these "model" years must be based on data that span the period from January through June rather than the whole year (even though the water budget must be calculated for the entire year) because this is the time period during which the degree of saturation has the greatest impact on the wetland. The degree of saturation during the early part of the year determines whether a site is going to act as a wetland during the growing season; the degree of saturation during the later part of the year determines whether wetland conditions can be maintained. Selection of representative wet, dry, and average years depends on the data available for a particular site, so wetland designers must justify the model years chosen. Whenever possible, representative wet-, dry-, and average-year data should be selected from the most recent 30 years of data. If fewer than 30 years of data are available for a site, then appropriate model years should be chosen for the reduced set of data. Note that a representative wet year is not necessarily a year with a higher than average amount of rainfall. For example, a severe storm event during an average or dry year could make that year seem wet in terms of the total precipitation amount.

Once daily values have been obtained, measured, or estimated for the entire model years for each component of the water budget, these data should be graphed both by day and by month. The graphs can then be used to evaluate the hydroperiod of the proposed wetland mitigation site with relation to the intended wetland elevation. The general steps to be taken to complete a water budget for a wetland mitigation site in New Jersey are shown in Figure 6.

Inputs and Outputs

The following sections describe data sources and methods that can be used to quantify the components of a wetland water budget. Because every mitigation project is unique in terms of scale and data and resource availability, a variety of methods is presented to quantify each of the components of a water budget. In addition, it is important to note that even with comprehensive data sources and advanced data-collection techniques, uncertainties are inherent in all data and methods used to determine water budgets.

Precipitation

Precipitation, either directly or indirectly, is a source of water for all wetlands, but its geographic distribution varies based on a host of climatic factors. In New Jersey, average annual precipitation ranges from about 40 in. along the southeastern coast to more than 52 in. in north-central parts of the State (Figure 7); in many areas, precipitation averages between 43 and 47 in. (Ludlum, 1983; Natural Resources Conservation Service, 1998). Measurable precipitation falls approximately 120 days throughout the year. Annual precipitation in New Jersey varies seasonally; the driest months typically occur in the fall, with an average of 8 days of measurable precipitation, whereas the remainder of the year is marked by an average of 9 to 12 days per month with measurable precipitation (Office of the New Jersey State Climatologist, 2007). A recent study by Watson and others (2005) has shown that over the past century, average annual precipitation in the northern portion of the State has undergone a statistically significant upward trend, or increase (Table 2). As a result, water-budget calculations that rely on historical (pre-1970) precipitation data from this part of the State may underestimate input from precipitation. Wetland designers need only account for the trend if relying on historical (early to mid century) data. More recent (post-1970) historical data, if available, should be used to obtain a reasonable estimate of precipitation input. No statistically significant increase in average precipitation was observed in the southern portion of the State over the last century (Watson and others, 2005).

Data Sources

Local weather stations are a prime resource for precipitation data. As shown in Figure 8, precipitation data are readily available for several weather station networks maintained throughout New Jersey. Depending on the instrumentation at a particular station as well as the availability of data summaries, precipitation data can be retrieved at yearly, monthly, daily, or hourly time intervals, and in some cases as real-time data. Much of the weather-station data for New Jersey is available through the National Climatic Data Center (http://www.ncdc.noaa.gov/oa/climateresearch.html), the Office of the New Jersey State Climatologist (http://climate.rutgers.edu/stateclim/), and the regional Climate Data Center at Cornell University in Ithaca, New York. Recent (2003-07) daily values can be accessed at http://climate.rutgers.edu/njwxnet/. In addition, the USGS operates a network of weather stations where data are collected at 15-minute intervals; these data are available in real time at http://waterdata.usgs.gov/nj/nwis/current?type=weather. Another source of precipitation data is the National Weather Service's web site for the Middle Atlantic Forecast Center, http://www.erh.noaa.gov/er/marfc/Maps/precip.html, which provides county-wide precipitation departure maps and data dating back to 1995. Precipitation data also are available though the South Jersey Resource Conservation and Development Council (SJRC&D), which hosts a network of 20 weather stations throughout southern New Jersey. Data from this network are available online at www.sjrcd.org/index.html. Lastly, precipitation data for several weather stations in New Jersey that are maintained by the National Air Deposition Program (NADP) can be accessed at http://nadp.sws.uiuc.edu/sites/sitemap.asp?state=nj. Table 1-1 (Appendix 1) lists general information about each of the weather stations in New Jersey, including dates of data collection and the sponsoring agency's station identification number.

Data Methods

Each weather station represents a single precipitation point. Examining data from a nearby, representative weather station is the method that is most often used to estimate precipitation input into a wetland system. Precipitation estimates for a particular area--for example, a nearby wetland--that are based on a single data point, however, may be subject to substantial error and uncertainty because of the spatial variability associated with precipitation. This may pose a problem in cases where precipitation is the driving input to a wetland system and a more precise estimate is needed. In order to achieve a more accurate representation of areal precipitation (the average depth of precipitation over a specific area), data from a network of stations can be used (National Weather Service, 2003). Three methods commonly used to calculate the average precipitation in a watershed, based on multiple precipitation points, are the arithmetic average, Thiessen polygon, and isohyetal methods (Dunne and Leopold, 1978).

The arithmetic average technique calculates areal precipitation using point precipitation data from each station on which the analysis is based (National Weather Service, 2003). This technique is suitable in areas where the rain-gage network is uniformly distributed (Fetter, 2001) and in areas of moderate topographic relief (Dunne and Leopold, 1978).

Unlike the arithmetic average method, in which the value from each precipitation station has the same weight, the Thiessen polygon method is an area-weighted method suitable for regions that are characterized by a non-uniform distribution of precipitation gages. The Thiessen polygon method is a graphical technique based on the idea that, for each point in a specified area, the best estimate of precipitation is the measurement physically closest to that point. On a map, neighboring data-collection stations are connected by lines, and perpendicular bisectors are drawn at the midpoint of each connecting line (Fetter, 2001). The bisectors are then joined to form polygons around each station. The area of each polygon is measured and the resultant value is used as the weighting factor to determine areal precipitation. The advantage of this method is that the polygons only need to be created once, allowing for repeated use across multiple precipitation events; the disadvantage is that it does not account for topographic influences. Differences between arithmetic and Thiessen averages are greatest for non-uniform storms when the polygon areas differ widely.

The isohyetal method, another area-weighted method, also is commonly used to estimate precipitation in regions where the rain-gage network is not uniformly distributed (Fetter, 2001). Using this method, lines of equal precipitation (isohyetal lines, or isohyets)--as determined from the rain-gage network--are drawn on a map. The area between adjacent isohyets is then measured and applied as the weighting factor to determine the average precipitation for a given area (Figure 9). The isohyetal method is considered the most accurate method for computing mean precipitation and is most suitable for large areas with many rain gages; however, the isohyets must be redrawn for each analysis, which may be time consuming (Fetter, 2001).

Although these methods may be more accurate than a single point estimate, they may not be viable options (without rain-gage installation) in many cases because they require that at least three rain gages are present within the watershed. It may be difficult to find multiple weather stations in a single watershed and with enough data during common years for these methods to be used. In this case, data from a representative station should be used.

Water-Budget Steps

The steps used to quantify the precipitation portion of a wetland water budget are outlined in Figure 10. At a minimum, daily values from a weather station that most closely represents the mitigation site (in terms of precipitation events) must be obtained. The representative station should be selected by analyzing historical precipitation data. The representative station often is the one closest to the mitigation site, but in some instances a more distant station may be preferable. For example, if the proposed mitigation site and the nearest weather station are located on opposite sides of a ridge, a weather station that is farther from but on the same side of the ridge as the proposed site may more closely represent the proposed mitigation site in terms of precipitation events. Another example in which it may be inadvisable to use data from the nearest weather station is when historical data from that station are insufficient to adequately illustrate representative wet, dry, and average conditions.

Once a representative station has been identified, the period of record must be examined and data from representative wet, dry, and average precipitation years must be obtained. The weather station and the model years selected must be specified and justified in the water budget. If it is advantageous to calculate areal precipitation for the proposed mitigation site using one of the methods described above, it should be calculated for representative wet, dry, and average conditions. Finally, tabulate and graph the daily and monthly precipitation values.

Surface Water

Surface runoff in New Jersey varies seasonally. A combination of abundant rainfall, saturated soil, low evapotranspiration, and snowmelt may cause high rates of runoff during March and April. For this reason, spring flooding is common. Runoff rates from May through October tend to be low as a result of increased evapotranspiration and increased ability of the soils to absorb water. During the fall, runoff typically increases and evapotranspiration decreases after the first killing frost. The period from December through March is marked by variable runoff rates depending on rain and snow events as well as ambient air temperatures (U.S. Geological Survey, 1986).

Data Sources

The main resource for surface-water data in New Jersey is the USGS, New Jersey Water Science Center. The USGS maintains a network of surface-water stations throughout the State at which stream stage and discharge are monitored. The USGS has been measuring streamflow in various streams in New Jersey since 1897 (Gillespie and Schopp, 1982), and several stations have been in operation since the 1920s or 1930s (Watt, 2000). In any given year, about 90 to 110 USGS streamflow-gaging stations are in operation in New Jersey (Watt, 2000). At these sites, water levels are recorded continuously and discharge measurements are made every 6 to 8 weeks. The USGS also maintains a network of crest-stage gages, which measure only the highest water level that occurred between visits by USGS personnel. In addition, the USGS operates a network of low-flow partial-record sites, which measure flow during periods of base flow--defined as 3 days of no rain in the northern part of the State and 5 days of no rain in the southern part of the State (Watt, 2000). Also, several networks of tide-gaging stations measure tide height. The locations of most types of surface-water data-collection sites in New Jersey are shown in Figure 11. Corresponding information for each site is found in Table 1-2 (Appendix 1). The USGS also has data from several discontinued streamflow-gaging stations. Although measurements are no longer made at these sites, historical data may be of use.

Stage and discharge information for all stations is published by the USGS annually in its Water-Resources Data Report, which is available at http://nj.usgs.gov/. In the 2006 **water year**, the USGS, New Jersey Water Science Center, maintained and published records for 108 continuous discharge-gaging stations, 31 tidal crest-stage gages, 21 reservoirs, and 42 diversions. Discharge measurements also were made at 298 low-flow and miscellaneous sites during the water year (Shvanda, 2007). Real-time data for selected sites are posted at http://waterdata.usgs.gov/nj/nwis/rt.

The U.S. Federal Emergency Management Agency (FEMA) is another source of surface-water data. Overflow data for streams are available through the Agency's flood frequency reports, which can be found at http://www.fema.gov/library/index.jsp.

Data Methods

An adequate assessment of surface-water input is important for all wetlands, but for riverine and other surface-water-driven wetlands it is critical. Contributing non-channelized flow must be quantified for all sites, and channelized flow must be quantified for sites that receive input from this source as well.

Non-Channelized Flow

On-site field measurements typically are not used to quantify the amount of non-channelized flow that enters a wetland system from contributing upland areas. Instead, one of several simple model approaches can be used to determine the volume of surface water emanating from a watershed. One such approach, the runoff curve number (CN) method, was developed by the U.S. Department of Agriculture's Soil Conservation Service (SCS), now called the Natural Resources Conservation Service (NRCS). This method is widely used to estimate the amount of runoff from a rainfall event, and is most applicable in small- to medium-sized watersheds. The runoff equation is

$$Q = (P - I_a)^2/(P - I_a) + S$$

where

Q = runoff (in.)

P = rainfall (in.)

S = potential maximum retention after runoff begins (in.)

I_a = initial abstraction (in.), the amount of water that will saturate the soil before runoff begins.

The CN method is based on soil type, plant cover, land use, and initial degree of saturation. The first step of the CN method is to determine the drainage area of the contributing watershed. Once this number is calculated, the watershed is divided into land-use types. Next, the appropriate CN for each land use is determined from U.S. Department of Agriculture (1986, Table 2-2a) and a single area-weighted CN is calculated for the entire watershed. The overall CN for the watershed can then be substituted into the following equation to obtain a value for potential storage, S

$$S = 1000/CN - 10.$$

By using this equation, runoff can then be calculated as

$$Q = (P - 0.2S)^2 / (P + 0.8S).$$

This is a variation of the equation above from which I_a has been removed as an independent parameter to produce a unique runoff amount (U.S. Department of Agriculture, 1986).

The SCS runoff curve number method is designed for a single rainfall event. To calculate daily surface-water input values, the minimum 24-hour rainfall amount necessary to produce runoff must first be determined from the above formula or from the CNs and Figure 12. The amount of runoff for each day for which precipitation exceeded the minimum amount necessary to produce runoff is then determined.

The U.S. Department of Agriculture's Technical Release 55, commonly referred to as the "TR-55 method", was developed to enhance the SCS runoff curve number method, specifically for calculation of runoff in urbanized settings (U.S. Department of Agriculture, 1986). Complete details of the TR-55 method are found at:

http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Tools_Models/WinTR55.html.

In addition, the NRCS offers a series of online training modules related to hydrologic characteristics; training modules are available for both the SCS runoff curve number methods and the TR-55 method, and can be accessed at:

http://www.wsi.nrcs.usda.gov/products/W2Q/H&H/Training/trng_ser.html.

Channelized Flow

A channel is any open conduit either naturally or artificially created which periodically or continuously contains moving water, or which forms a connecting link between two bodies of water (Langbein and Iseri, 1960). If the surface-water input from the watershed to the wetland is in the form of channelized flow, direct measurements can be made using weirs, flumes, and stage-gaging techniques. Refer to Rantz and others (1982a, 1982b) for a comprehensive overview of methods used to make stage and discharge measurements as well as methods used to compute discharge. (Note that a permit may be required to establish equipment along a stream bank). Accurate on-site streamflow measurements can be valuable as input data for surface-water models and for comparison with available reference data.

Under circumstances in which direct-discharge measurements cannot be made or are otherwise not available, the quantity of surface-water inflow to and outflow from a wetland system can be calculated indirectly. For example, the cross-sectional average discharge for free-flowing sections of a channel can be calculated by way of the continuity equation $Q = VA$, where

Q = discharge (ft^3/s)

V = velocity (ft/s)

A = cross-sectional area of flow (ft^2).

The velocity term in the above equation can be calculated from stream characteristics using the Manning equation:

$$V = (1.49/n)\, R^{2/3}\, S^{1/2}$$

where

V = velocity (ft/s)

n = roughness factor

R = hydraulic radius (ft)

S = slope (ft/ft).

Chow (1959) presents a list of suggested values for Manning's roughness coefficients, which are based on the surface material that lines the channel. Furthermore, the hydraulic radius (R) is calculated by dividing the cross-sectional area of flow (A) by the wetted perimeter (Wp), such that R = A/Wp.

Hydrologic models can be a valuable tool for estimating the value of water-budget components. A hydrologic model is a simplified representation of a hydrologic system. Some examples of surface-water models that can be applied to channelized flow are described below. Selection of the most appropriate model depends on the ultimate objective of the surface-water study. For example, SWMM is a rainfall-runoff model that is used to predict runoff from a given rainfall event(s). HEC-RAS, a hydrodynamic flood-routing model, can be used to predict downstream water-surface profiles and flow under specific upstream conditions. Other surface-water models, including StreamStats and MOVE1 use statistics such as correlation and regression equations to synthesize or extend a hydrologic record. Although models can be informative and helpful, their limitations should be considered. For example, some models require large amounts of data for calibration and some can be expensive to implement.

The Storm Water Management Model (SWMM) is a rainfall-runoff simulation model developed by the USEPA. This model can be used to simulate the quantity of runoff generated by single or multiple precipitation events from primarily urban areas (U.S. Environmental Protection Agency, 2007). SWMM is data-intensive, but works well for complex surface-water systems—for example, systems in which water may be routed through several areas before reaching the mitigation site (Peter Kallin, Rutgers Cooperative Research and Extension, oral commun., 2007). Precipitation data from representative wet, dry, and average years and streamflow data collected at 15-minute intervals can be used to calibrate the model and make it site-specific. Additional information about SWMM can be found at http://www.epa.gov/ednnrmrl/models/swmm/index.htm.

The Hydrologic Engineering Centers River Analysis System (HEC-RAS) is another surface-water model that can be used to evaluate flooding characteristics of streams (U.S. Army Corps of Engineers, 2008). The HEC-RAS system was designed to aid hydraulic engineers in channel-flow analysis and floodplain determination. Specifically, it allows for one-dimensional hydraulic analysis of steady flow, unsteady flow, sediment transport, and water quality. Water-surface profiles and flow—simulated using models such as HEC-RAS—can be used to estimate the frequency and magnitude of inundation of mitigation sites by floodwaters. Information about the HEC-RAS model, including a link to download the program, can be found at http://www.hec.usace.army.mil/software/hec-ras/hecras-hecras.html.

In some cases, surface-water data-collection stations may be located near a proposed mitigation site. Several surface-water models have been developed that are capable of "record extension" such that data collected at existing data-collection stations can be used to predict hydrologic conditions at ungaged sites. For example, the USGS, in cooperation with the Environmental Systems Research Institute, Inc. (ESRI), has developed a GIS-based method to relate streamflow data from USGS data-collection stations to ungaged locations on the same stream. This program—called StreamStats—is a web-based tool that allows users to obtain streamflow statistics, drainage-basin characteristics, and other information for user-selected sites--gaged as well as ungaged--along a stream (Ries and others, 2004). Examples of streamflow statistics include mean annual flow and the 100-year flood; examples of basin characteristics include land-use percentages and stream slope (Ries and others, 2004). State-specific regression equations are used to compute these statistics for ungaged sites. For more information on StreamStats, visit http://water.usgs.gov/osw/streamstats/index.html. Click on the "State Applications" link to access New Jersey's StreamStats web site.

Another means of surface-water record extension is offered by the Maintenance of Variance Extension Type 1 (MOVE1) method of correlation analysis, which can be used to estimate low-flow statistics at stream sites for which a continuous record of streamflow is not available (Watson and others, 2005). In terms of wetland mitigation, this method can be used to relate instantaneous base-flow measurements made at a stream location adjacent to a mitigation site to measurements made at a long-term continuous-record gaging station located in a basin with similar hydrologic conditions. High flows that are likely to crest the streambank and inundate the wetland can then be extrapolated. The USGS maintains a network of low-flow partial-record stations (Figure 13). A subset of these stations is selected each year to be measured two to three times during base-flow conditions. These low-flow partial-record stations may yield data useful to a mitigation study if a station is in close proximity to the mitigation site.

Streamflow statistics for each USGS continuous-record streamflow-gaging station and partial-record station for water years 1897-2003 are available at http://pubs.usgs.gov/sir/2005/5105/. A detailed explanation of the MOVE1 method can be found in Helsel and Hirsch (2002).

Water-Budget Steps

The steps used to quantify the surface-water portion of a wetland water budget are outlined in Figure 14. In summary, all non-channelized surface flow that enters the mitigation site from the surrounding landscape should be quantified using the runoff curve number and TR-55 methods. Also, any channelized surface-water input to the wetland system must be quantified using historical data, data collected on-site, interpolated data, or a combination of all three. If no historical data are available for the stream, data collected on-site, such as discharge or stage data, are required. Use of numerical models to quantify channelized flow may minimize the need to collect data at a particular site. For example, as mentioned, the StreamStats program can be used to calculate discharge, or flow rate, for any point along a stream; however, errors associated with model calculations need to be recognized and understood, and field measurements may be necessary to verify the program's output.

The sum of channelized and non-channelized flow values is the overall surface-water input to the wetland system. Daily and monthly surface-water flow values must be calculated for representative wet, dry, and average years. These values should be converted to units of depth per time and graphed with the other components of the water budget.

Ground Water

Understanding the occurrence and movement of water in an almost infinitely complex subsurface environment is challenging (Heath, 1983). Accurately measuring and calculating the ground-water component of wetland water budgets can be time consuming and expensive (Carter and others, 1979; Carter, 1986; Pierce, 1993); however, making ground-water flux measurements provides useful information. The challenge is one of anticipating what the flux may be in a wetland that will be constructed as opposed to a wetland that is already in existence.

The process of understanding the importance of the ground-water component for a particular location should start with researching historical ground-water information about a site location. This is a good way to provide an initial screening to determine the amount of data that needs to be collected on-site to fully understand ground-water fluctuations and ground-water movement throughout the mitigation site. It is essential to collect data on-site in order to determine the complexity of the ground-water environment because the ground-water environment is hidden from view. Once on-site data have been collected using methods described below, engineering calculations and models can be used to determine ground-water inputs to and outputs from the wetland system.

Darcy's Law

Darcy's Law is the fundamental equation that governs the movement of water through a porous medium. Water flows from high elevation to low elevation and from high pressure to low pressure. According to Darcy's Law (Fetter, 2001), the rate of flow is directly proportional to the difference in hydraulic head between two points (as determined by differences in elevation and pressure), and inversely proportional to the length of the flow path between those two points, such that

$$Q = KA\,(\Delta h/L)$$

where

Q =volumetric discharge, or flow rate (L^3/T; ft^3/d or m^3/d)

K = proportionality constant, called the **hydraulic conductivity** (L/T; ft/d or m/d)

A = cross-sectional area (L^2; ft^2 or m^2)

Δh = difference in hydraulic head (L; ft or m)

L = flow length (L; ft or m).

Using Darcy's Law, the rate of flow of ground water into or out of a wetland can be estimated from measurements made on-site, because a number of the above parameters can be measured in the field following installation of wells. For example, the difference in hydraulic head, Δh, can be determined from water-level measurements made in two different wells, where L represents the distance between the wells. The cross-sectional area, A, is calculated as the confined aquifer's saturated thickness, multiplied by the aquifer width. The hydraulic conductivity, K, must be estimated to complete the calculation; several methods that can be used to make this estimate based on data collected in the field are described in later sections. Hydraulic conductivity is typically greater in the horizontal direction than in the vertical direction as a consequence of bedding planes, laminae, and other sedimentary structures.

A form of Darcy's Law that is used to quantify flow through **unconfined aquifers** is Dupuit's Equation (Fetter, 2001):

$$q' = \frac{1}{2} K \left((h_1^2 - h_2^2)/L \right)$$

where

q' = flow per unit width (L^2/T; ft^2/d or m^2/d)

K = hydraulic conductivity (L/T; ft/d or m/d)

h_1= head at the origin (L; ft or m)

h_2= head at L (L; ft or m)

L= flow length (L; ft or m).

For more information on the components of Darcy's Law and ground-water flow, refer to Heath (1983) and Bennett (1976).

Data Methods

Ground-water data should be collected as part of a site evaluation even if ground water is projected to have a minor impact on a wetland's overall water budget. If the wetland is one in which ground water is a key component, such as a ground-water depression wetland, then a thorough investigation is imperative (Carter and others, 1979; Carter, 1986; Pierce, 1993). A variety of data-collection techniques can be employed in the field to characterize a site's subsurface environment. Brief summaries of some of these data-collection techniques are provided below; information obtained from the techniques includes values of hydraulic conductivity, infiltration rate, and water level. This information can then be used to estimate the rate and quantity of ground-water inflow to and outflow from a wetland.

Soil Borings and Test Pits

Soil borings and test pits can be used to determine subsurface characteristics and to obtain samples of the soil column. Soil borings are typically done manually, are restricted to shallow depths, and allow for characterization of subsurface geological properties, whereas test pits are typically dug by mechanical equipment and used for direct measurement of infiltration rate. Soil characteristics as determined from borings and test pits can then be used to estimate hydraulic conductivity. In addition, soil borings and test pits offer evidence of seasonal variations in the water table. Soil borings and digging of test pits should be completed prior to installation of wells.

Ground-Water Wells and ***Piezometers***

Ground-water levels fluctuate over time, often as a result of seasonal variations in rainfall and climatic events such as drought. In general, water levels are highest in winter and early spring as a result of little or no evapotranspiration, low temperatures, snowmelt, and spring rains. Water levels typically fall during summer months and evapotranspiration rates increase as water is used for irrigation and recreation. Water levels continue to decline and usually reach their lowest levels in late fall (Watt, 2000). Water levels in wells that are completed in unconfined aquifers ("water-table" wells) typically vary more than in wells completed in confined aquifers (assuming non-pumping conditions) because unconfined wells lack the buffer of an overlying confining layer to dampen the effects of short-term climatic changes and infiltration of precipitation.

The variability of the local water table in and around a wetland mitigation site must be known in order to predict the water supply needed for critical times. One way to do this is to install an adequate number of wells or piezometers on-site and monitor the water-level changes to gain an understanding of the short-term water-table fluctuations at the site. These data can then be compared to available data on regional water-table fluctuations to better estimate likely long-term fluctuations in water levels at the wetland site. Data from representative wet, dry, and average years should be considered to account for climatic variability. If water-level data collected on-site are the only water-level data available for a site, 1 or 2 years of data may be insufficient to evaluate the long-term water-table variability at that location (Pierce, 1993). (Note that all wells should be constructed, maintained, abandoned, and sealed in accordance with N.J.A.C. 7:9D, effective 4/2/2007 (New Jersey Department of Environmental Protection, 2007).)

The components of a typical ground-water observation well are shown in Figure 15. Observation wells include both those that allow for measurement of the water table and those that allow for measurement of hydraulic head below the water table. The latter are known as piezometers and are constructed such that the screened part of the piezometer is isolated from the surface. A piezometer, like a monitoring well, includes a screen, a gravel pack, and an annular seal. A limitation of piezometers is that because they have a shorter screen, they can be used to measure the hydraulic head of only an isolated part of the aquifer. An advantage of piezometers is that they yield information about the vertical and horizontal components of ground-water flow; such information cannot be obtained from water-table wells alone. Another advantage of piezometers is the cost savings resulting from the shorter casing and simpler installation technique. A disadvantage to piezometers is that the liklihood of misinterpretation of the data is increased because the screen is shorter. For example, a piezometer can misrepresent data when water is perched above an impermeable clay lens that overlies an aquifer that supplies water to the wetland. Ground-water wells with a longer screen provide a better indication of the water-table surface.

The differences between, and uses and installation of, ground-water monitoring wells and piezometers in wetlands are described by the U.S. Army Corps of Engineers (2000) which can be accessed at http://el.erdc.usace.army.mil/wrap/pdf/tnwrap00-2.pdf

Section of Flow

For the purpose of this manual, a "section of flow" refers to a portion of a mitigation site that is uniform in terms of soil characteristics, topography, and **hydraulic gradient**, and in which ground-water flow can be assumed to be uniform. Each site has at least one representative section of ground-water flow. A simple site, such as a small riparian corridor that runs along one side of a stream, may have only one section of flow (Figure 16a), whereas a larger, more complex site may have multiple sections of flow (Figure 16b). The number and spatial extent of the sections of flow for a given site can be determined by examining different spatial data layers such as topography, soil type, land cover, surficial geology, and hydrography.

A minimum of three wells must be installed per section of flow to adequately assess the ground-water influences at a site. Although a minimum of two wells is needed to determine the gradient, three or more wells are needed to determine direction of flow. As the size or complexity of the mitigation site increases, it may be necessary to install multiple sets of wells to obtain an accurate representation of the water table. For example, if a proposed wetland mitigation site encompasses two sides of a stream, each with a different gradient, at least three wells must be installed on each side of the stream.

Water-Table Maps

Water levels measured in wells installed in an unconfined aquifer can be used to produce a water-table map, which is a two-dimensional representation of the water table, or the top of the saturated zone (Watt, 2000; Fetter, 2001). Water-table maps can be used to evaluate direction of flow, visualize hydraulic gradient, and interpolate water levels between wells. Because ground-water levels change with time, water levels used to construct a water-table map should be measured at approximately the same time. Using these water-level readings, contour lines of equal ground-water elevation can be drawn. The direction of ground-water flow typically is approximately perpendicular to the water-level contours on the water-table map. In northern New Jersey, where the rocks are fractured and folded, however, the direction of ground-water flow can be more difficult to determine (Watt, 2000).

Water-table maps also are useful in assessing the interaction between ground water and surface water. Where the water table intersects a stream, the water-table contour forms a “v” shape. For a gaining stream—one that receives ground-water discharge—the “v” points upstream because water is flowing into the stream. For a losing stream—one that loses flow to the ground-water system—the “v” points downstream because water is flowing from the stream into the stream banks (Watt, 2000). The difference between gaining and losing streams is shown in Figure 17.

Infiltrometers

Hydraulic-conductivity values are used with horizontal- and vertical-flow gradients to determine rates of ground-water flow; along with estimates of **porosity**, they can be used to determine ground-water flow velocity. Measurement of hydraulic conductivity can be difficult because values of this parameter can vary greatly even with minor changes in sediment characteristics. Hydraulic conductivity can be estimated through the use of infiltrometers, permeameters, and aquifer and slug tests.

An infiltrometer is a device used to measure the rate of water infiltration into the soil. One of the most commonly used types of infiltrometer is the ring infiltrometer, which measures infiltration capacity--the maximum rate at which infiltration can occur--over an area defined by a small cylindrical ring that is inserted into the soil (Dingman, 1994). Water is supplied to the ring until the soil becomes saturated and ponding occurs. From this point, the rate of infiltration can be determined by measuring the rate at which the level of ponded water decreases, or by measuring the rate at which it is necessary to add water to maintain a constant level of ponding (Dingman, 1994). The rate at which water enters the soil is measured for a given period of time and is related to the soil’s hydraulic conductivity (Dunne and Leopold, 1978).

There are two types of ring infiltrometers--single ring and double ring. Because water in a single infiltration ring can move vertically as well as laterally, the infiltration rate determined from a single ring may exceed the actual vertical infiltration rate. A double ring infiltrometer relies on an additional outer ring to create one-dimensional flow and, therefore, allows the vertical hydraulic conductivity to be quantified. Thus, the infiltration rate is approximately equal to the saturated vertical hydraulic conductivity.

The U.S. Army Corps of Engineers' Process Design for Land Treatment of Municipal Wastewater Manual presents information on these and other types of infiltrometers, including the sprinkler infiltrometer; this manual can be found at http://www.usace.army.mil/publications/eng-manuals/em1110-1-501/c-3.pdf.

Permeameters

Another method used to measure hydraulic conductivity, particularly for non-cohesive sediments such as medium- to coarse-grained sand, makes use of a constant-head permeameter (Fetter, 2001), an instrument in which water supplied from a constant-head reservoir moves through a sediment sample at a steady rate. The volume, V, of water that flows through the sample over a measured period of time, t, represents the discharge rate, Q, such that V/t = Q. Through substitution and simple rearrangement of Darcy's Law, the hydraulic conductivity of the sediment is then calculated using the following formula as found in Fetter (2001):

$$K = VL / (Ath)$$

where

K = hydraulic conductivity of the sediment sample (L/T; m/d)

V = volume of water discharging in time t (L^3; cm^3)

L = sample length (L; m)

A = cross-sectional area of sample (L^2; cm^2)

t = time (T; s)

h = hydraulic head (L; cm).

For cohesive sediments with low conductivities, such as silty fine sand, it is more appropriate to use a falling-head permeameter. Because the conductivity is low, a much smaller volume of water moves through the finer grained sediment (Fetter, 2001). A falling-head permeameter typically employs a smaller reservoir and, as its name suggests, the rate at which water is supplied to the sediment declines over time. In this case,

$K = d_t^2 L / d_c^2 t * \ln(h_o / h)$

where

K = hydraulic conductivity of the sediment sample (L/T; cm/s)

L = sample length (L; cm)

h_o = initial head in the falling tube (L; cm)

h = final head in the falling tube (L; cm)

t = time that it takes for the head to go from h_o to h (T; s)

d_t = inside diameter of the falling-head tube (L; cm)

d_c = inside diameter of the sample chamber (L; cm).

Aquifer and Slug Tests

An aquifer's hydraulic properties, including hydraulic conductivity, can also be estimated by conducting an aquifer test. Aquifer tests tend to be expensive and time consuming but often provide accurate results. An aquifer test reveals how water levels in an aquifer respond to ground-water withdrawals. During the test, water is pumped from a single "pumped" well at a constant rate. Water levels in the vicinity of the pumped well fall, and ground water from surrounding areas flows toward the pumped well in response to the newly created hydraulic gradient. Water levels measured in nearby observation wells before and during the aquifer test indicate the aquifer's time-drawdown response. From this time-drawdown relationship, hydraulic characteristics of an aquifer can be interpreted (Heath, 1983; Fetter, 2001). Aquifer tests can be performed under a variety of hydrologic circumstances, including equilibrium and non-equilibrium conditions or in a confined aquifer and or a leaky confined aquifer. For this reason, a wide variety of formulas is available for the analysis of aquifer-test data. Aquifer tests are expensive and may not be feasible in areas of low conductivity (Fetter, 2001). Refer to Kruseman and de Ridder (1990) for guidance on aquifer-test design and data analysis.

A slug test, a less expensive alternative to an aquifer test, is a means by which data from a single well can be utilized to estimate the horizontal hydraulic conductivity of the subsurface material--particularly that which lies in close proximity to the well. A slug test involves the instantaneous injection or withdrawal of a known volume or slug of water into a well (U.S. Environmental Protection Agency, 1994), which, in turn, causes a sudden rise or fall of the ground-water level (Fetter, 2001). Once the slug has been introduced to or removed from the well, resulting changes in the water level are monitored until equilibrium is reached (Bouwer and Rice, 1976; Bouwer, 1989). Like aquifer-test data, slug-test data can be analyzed using several different methods whose applicability depends on the hydraulic conditions of the aquifer.

Each test has advantages and disadvantages. For example, both aquifer and slug tests provide in situ field measurements of hydraulic properties but slug tests are less time-intensive and do not require pumped and observation wells (U.S. Environmental Protection Agency, 1994). However, slug tests require a clean wellpoint or screen (Freeze and Cherry, 1979)--that is, the wells must be properly developed.

Bouwer and Rice Slug-Test Method

The Bouwer and Rice (1976) slug-test method is widely used to analyze slug-test data to estimate hydraulic conductivity. The Bouwer and Rice method can be applied to open boreholes or to partially or fully penetrating screened wells. Using the Bouwer and Rice slug-test method, hydraulic conductivity is calculated as:

$$K = \frac{r_c^2 \ln(R_e/r_w) \ln(y_o/y_t)}{2 L_e t}$$

where

K = hydraulic conductivity (L/T; ft/d, m/d, or cm/s)

r_c = radius of the well section where the water level is rising (L; ft, m, or cm)

R_e = effective radial distance over which the head difference y is dissipated (distance from the well over which the average value of K is being measured) (L; ft, m, or cm)

r_w = radial distance between well center and undisturbed aquifer (r_c plus thickness of gravel envelope or developed zone outside casing) (L; ft, m, or cm)

L_e = height of perforated, screened, uncased, or otherwise open section of well through which ground water enters (L; ft, m, or cm)

y_o = y at time zero (L; ft, m, or cm)

y_t = y at time t (L; ft, m, or cm)

t = time since y_o (T; d or s).

Brown and others (1995) concluded that the Bouwer and Rice method tends to generate more accurate estimates of K than a commonly used alternative, the Hvorslev method (Hvorslev, 1951); however, they also found that the Bouwer and Rice method can underestimate K, with the greatest errors occurring when the top of the screen is near the water table.

The Soil Survey Manual (http://soils.usda.gov/technical/manual/) and the National Engineering Handbook (http://www.info.usda.gov/CED/), both available through the NRCS, offer additional, alternative methods for ground-water (and surface-water) data collection.

Numerical Ground-Water Flow Models

Under some circumstances in which water-table fluctuations are more complex or different than anticipated, it may be necessary to develop a separate water-table model (Pierce, 1993). A numerical ground-water flow model is a mathematical representation of an actual ground-water system that can be used to predict water levels as well as the direction and magnitude of flow. Models range from simple to very complex in terms of data-input requirements, calibration requirements, and data output. The selection of a model or analytical approach to a problem depends on the nature of the problem and the acceptable level of uncertainty in the model results. The acceptable level of uncertainty will depend on the mitigation objectives. The water budget itself cannot predict water levels or account for system complexities such as heterogeneity or the effects of hydrologic boundaries. Numerical modeling is a means to explicitly represent one or more hydrologic processes by solving the governing equations that describe them (Franke and others, 1987). If the wetland system is highly complex and the need for confidence in water levels is high, then a simple representation of the system might not be adequate. For example, a ground-water model is likely to be useful when predicting seasonal ground-water levels for a large, ground-water-supported wetland in a bedrock-bounded valley-fill setting that is marked by variable glacial geologic characteristics and a network of meandering streams. A large and/or highly heterogeneous site may require a more complex model in order to satisfy mitigation requirements. In practice, the feasibility of using a numerical ground-water flow model may depend on the existence of a previously calibrated model that is both appropriate and readily available.

The first step in ground-water modeling is to develop a "conceptual model" of the ground-water system (Franke and others, 1987)--a qualitative, physical description of how and where water enters the ground-water system and how and where it leaves (Reilly, 2001). The next step is to determine the inputs, parameters, and initial and boundary conditions for the model. Flow that enters the modeled area represents the input. Topography, thicknesses of soil layers, horizontal and vertical hydraulic conductivity, porosity and storage coefficient, and capillarity of the unsaturated zone are model parameters. The most critical step--and the part most subject to error--is to accurately determine the appropriate initial and boundary conditions for the model (Franke and others, 1987). Once the conceptual model has been developed and boundary conditions have been established, the conceptual model can be transformed into a numerical model and calibrated, such that predicted water levels match measured water levels. Anderson and Woessner (1992) provide a comprehensive description of ground-water modeling, including an outline of the steps required to develop a ground-water flow model.

MODFLOW

MODFLOW, the most commonly used numerical ground-water flow model, is a three-dimensional model that was first released in 1984 by the USGS. The program is used to simulate steady (average) and nonsteady (seasonally fluctuating) ground-water flow in an irregularly shaped flow system in which aquifer layers can be confined, unconfined, or a combination of confined and unconfined (McDonald and Harbaugh, 1988). The model also can simulate ground-water flow associated with wells, recharge, evapotranspiration, drains, and rivers. The governing partial differential equation used in MODFLOW is

$$\frac{\partial}{\partial x}\left[K_{xx}\frac{\partial h}{\partial x}\right]+\frac{\partial}{\partial y}\left[K_{yy}\frac{\partial h}{\partial y}\right]+\frac{\partial}{\partial z}\left[K_{zz}\frac{\partial h}{\partial z}\right]+W=S_S\frac{\partial h}{\partial t}$$

where

K_{xx}, K_{yy}, and K_{zz} = values of hydraulic conductivity along the x, y, and z coordinate axes, respectively (L/T)

h = potentiometric head (L)

W = volumetric flux per unit volume representing sources and/or sinks of water for which negative values are extractions and positive values are injections (T^{-1})

S_S = specific storage of the porous material (L^{-1})

t = time (T).

The most recent version of MODFLOW, MODFLOW-2005, is currently (2008) available for download at http://water.usgs.gov/nrp/gwsoftware/modflow2005/modflow2005.html. In addition, a user guide by Harbaugh (2005) explains in detail the physical and mathematical concepts on which the model is based, describes how those concepts are incorporated in the modular structure of the computer program, and provides instructions for using the model and details of the computer code. This user guide is available at http://pubs.usgs.gov/tm/2005/tm6A16/.

Relating Water-Level Data from Long-Term Monitoring Wells to Water-Level Data Collected On-Site

An understanding of the long-term water-table variability is important for all wetland mitigation project design, but it is imperative for ground-water driven wetland systems. Relating short-term ground-water-level data collected on-site to water levels from a similarly situated long-term data-collection station may provide insight into the long-term pattern of local water-table fluctuations at the site of interest. Zampella and others (2001) conducted a study in the forests of the Pinelands area of the New Jersey Coastal Plain in which simple linear regression together with long-term water-level data sets collected at reference sites were used to estimate long-term hydroperiods at test sites for which only short-term data sets were available. Agreement was found both between measured and predicted water levels and between measured and estimated frequencies of near-surface saturation at the test sites during the growing season. Socolow and others (1994) estimated long-term high, median, and low ground-water levels at sites of interest in Rhode Island using a single water-level measurement made at the site of interest in combination with a long-term water-level record at an observation well. Although this study was conducted in Rhode Island and is based on several assumptions (water levels will fluctuate in the future as they have in the past; water levels fluctuate seasonally) the technique described can be applied to other geographic regions, including New Jersey, depending on data availability and provided that the reference sites are similar to the mitigation site with respect to hydrogeologic and climatic conditions.

Data Sources

The Natural Resources Conservation Service's Web Soil Survey (WSS), an interactive web application that provides access to the most up-to-date soil information, is a source of data that are useful in assessing the ground-water component of a wetland's water budget. At the WSS web site, a user can obtain information about the soil of a specific geographic area of interest, such as a planned wetland mitigation site, in terms of its physical, chemical, and erosional properties as well as its hydraulic properties (depth to water table, flooding frequency, drainage class, and saturated hydraulic conductivity). The WSS can be accessed at http://websoilsurvey.nrcs.usda.gov/app/.

The USGS has maintained a network of observation wells in New Jersey since 1923 for the purpose of monitoring changes in ground-water levels. During the 2005 water year, water levels were measured in 49 water-table wells, 37 of which were equipped for continuous water-level monitoring; the other 12 wells were measured manually from two to six times per year (Jones, 2006). Network wells completed in unconfined aquifers are shown in Figure 18; corresponding information for each site is found in Table 1-3 (Appendix 1). Also shown in Figure 18 are wells in bedrock and valley-fill sediments that also may show daily water-level fluctuations from precipitation. Water levels for each of the stations within the network are published by the USGS annually in its Water-Resources Data Report, the most recent of which is available at http://nj.usgs.gov/. Historical daily values, which depend on the station's period of record, are available at http://waterdata.usgs.gov/nj/nwis/gw.

As part of a statewide Drought Monitoring Network established in cooperation with the NJDEP, the USGS maintains a network of 20 wells that are equipped with satellite telemetry which allows for real-time continuous ground-water-level monitoring. Data for these 20 sites, which also are part of the National Ground Water Climate Response Network, can be accessed at http://groundwaterwatch.usgs.gov/StateMaps/NJ.html.

Water-Budget Steps

The steps used to quantify the ground-water portion of a wetland water budget are outlined in Figure 19. In summary, historical data should be evaluated to identify data gaps and determine the data needs for the mitigation site. Historical ground-water data also may be used to generate a long-term record from short-term measurements and to determine representative wet, dry, and average conditions. Available data on the site's topography, soil type, surficial geology, and hydrography should be examined to determine the number of sections of ground-water flow at a site. A minimum of three wells must be installed per section of flow to characterize water-table fluctuations and ground-water movement throughout the site. The hydraulic conductivity of each section of flow also must be determined, from soil borings, wells, infiltrometers, permeameters, and/or aquifer and slug tests. When data collection is complete, engineering calculations such as Darcy's Law and models such as MODFLOW can be used to determine ground-water inputs to and outputs from the wetland system. Daily and monthly ground-water values can then be tabulated and graphed for representative wet, dry, and average years. An additional period of data collection may be needed if the water-level fluctuations are not adequately documented or if the wetland is ground-water driven.

Evapotranspiration

Evapotranspiration (ET) is one of the most challenging components of a wetland's water budget to compute; obtaining accurate measurements of transpiration is particularly difficult (Carter, 1996). ET changes over time as vegetation communities evolve and mature. A variety of methods are available to estimate ET, including direct-measurement procedures and empirical formulas; however, the accuracy and practicability of these methods are debatable.

Direct-Measurement Techniques

One direct measurement technique to measure ET employs an evaporation pan. Using this method, the evaporative loss from a standard class “A” pan is typically determined by measuring the decrease in water level, by measuring the change in weight, or by measuring the volume of water needed to replace water lost over a period of time (Mitsch and Gosselink, 2000). A monthly variable crop coefficient, *k*, can be used to convert the pan evaporation value (E_{pan}) to **potential ET** (ET_o), such that $ET_o = kE_{pan}$ (Mao and others, 2002). Doorenbos and Pruitt (1977) provide ranges of crop coefficients suitable for a variety of climate and site conditions; a recommended value for *k* is 0.7 (Mao and others, 2002). Winter (1981) also discusses the use of pan coefficients. Because the water surface of an evaporation pan represents a saturated environment, pan evaporation estimates often differ from those for vegetated surfaces; therefore, the potential ET result is generally viewed as a reference value.

Another direct measurement technique to determine ET makes use of a lysimeter, which is a device used to measure the amount of water that flows into and out of an enclosed volume of soil and plants (Dingman, 1994). The soil and plant composition within the lysimeter should be representative of the surrounding area. In addition, any moisture drained from the soil must be accounted for. Fetter (2001) describes the following equation for use with a lysimeter:

$$E_T = S_i + P_R + I_R - S_f - D_E$$

where

E_T = evapotranspiration for a period

S_i = initial volume of soil water

S_f = final volume of soil water

P_R = precipitation into the lysimeter

I_R = irrigation water added to the lysimeter

D_E = excess moisture drained from the soil.

Changes in the soil-moisture storage within the lysimeter indicate the amount of water that is lost from the enclosed area through ET (Fetter, 2001). Although lysimeters may offer accurate estimates of ET, they are both time consuming and costly to operate.

Daily, or diurnal, water-table fluctuations also can be used to determine ET rates in some wetlands. As mentioned earlier, ET is highest during the day when solar radiation is at its peak and vegetation is actively transpiring, and lowest at nighttime when sunlight is absent. Diurnal methods used to estimate ET in wetlands are based on the idea that the water level is near the root zone and fluctuations in ground water or surface water reflect the diurnal ET cycle. For many of these methods, ET is considered to be negligible between midnight and 4:00 A.M., and the rate of recharge for a wetland can be measured during this same time period (Mitsch and Gosselink, 2000; Nachabe and others, 2005). Mitsch and Gosselink (2000) describe one diurnal method with the equation:

$$ET = S_y\,(24h \pm s)$$

where

ET = evapotranspiration (mm/d)

S_y = **specific yield** of aquifer (1.0 for standing-water wetlands, < 1.0 for ground-water wetlands

h = hourly rise in water level from midnight to 4:00 A.M. (mm/hr)

s = net fall or rise of water table or water surface in one day.

Nachabe and others (2005) describe an alternative direct-measurement technique—also based on diurnal fluctuations—that can be used to estimate ET, specifically in shallow-water-table environments. This method relies on the use of soil moisture sensors to estimate diurnal fluctuations in total soil moisture through the root zone and below the water table (Nachabe and others, 2005). Using this method, the subsurface flow rate, *Q*, is calculated from the recovery rate of soil moisture between midnight and 4:00 A.M. Daily ET losses can then be calculated using the following equation:

$$ET = TSM_j - TSM_{j+1} + 24 * Q$$

where

TSM_j = total soil moisture at midnight on day j

TSM_{j+1} = total soil moisture 24 hours later

Q = subsurface flow rate.

Unlike the diurnal method described previously, this method does not require the estimation of specific yield.

Meteorological Methods

Several empirical formulas also are available to compute ET in wetlands; these formulas make use of a variety of meteorological data, including rainfall, air temperature, solar radiation, wind speed, and relative humidity. Depending on the data-input requirements, meteorological methods used to estimate ET can be categorized into three broad groups--temperature-based, radiation-based, and combination.

One example of a temperature-based formula is the Thornthwaite (1948) equation, which estimates potential ET expressed as (Pierce, 1993; Dunne and Leopold, 1978):

$$ET_i = 1.6(10T_i/I)^a$$

where

ET_i = potential evapotranspiration for month *i* (cm/mo)

T_i = mean monthly temperature (°C)

I = annual heat index = $\sum(T_i/5)^{1.5}$

$a = 0.49 + 0.0179I - 0.0000771I^2 + 0.000000675I^3$.

The calculated ET_i must then be multiplied by a correction factor to adjust for latitude and month (to account for variations in duration of sunlight) as listed in Table 3 (Dunne and Leopold, 1978). The Thornthwaite method has had mixed success in wetland environments (Mitsch and Gosselink, 2000), but it is still widely used because the calculation only requires measurement of a single meteorological variable that is generally available or otherwise easy to measure--air temperature.

Two additional temperature-based methods are the Hamon (1963) method, which requires mean daily temperature values, and the Hargreaves-Samani (1985) method, which requires daily maximum and minimum temperatures (Lu and others, 2005).

The Penman-Monteith equation is a "combination" formula that is used to estimate evapotranspiration. This formula originated with an equation for evaporation developed by Penman (1948) for areas of open water. The formula was modified by Monteith (1965) to account for additional resistance from the plant canopy (Sumner, 1996). The combined Penman-Monteith equation, as described by the Food and Agriculture Organization of the United Nations (FAO), is

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)}$$

where

λET = evaporative latent heat flux [MJ/(m^{2}d]

R_n = net radiation at the crop surface [MJ/m^2d]

G = soil heat flux density [MJ/m^2d]

e_s = saturation vapor pressure [kPa]

e_a = actual vapor pressure [kPa]

$e_s - e_a$ = saturation vapor pressure deficit [kPa]

ρ_a = mean air density at constant pressure [kg/m^3]

c_p = specific heat of the air (J/gm°C)

Δ = slope vapor pressure curve [kPa/°C]

γ = psychrometric constant [kPa/°C]

r_s = (bulk) surface, or canopy, resistance [s/m]

r_a = aerodynamic resistance [s/m] .

As a result of the many variables--most of which are not available at weather stations--that must be determined, the Penman-Monteith combination method is likely to be infeasible for many mitigation projects. However, it and its derivatives have been used by wetland designers in New Jersey to estimate ET, and it is used in one of the data sources mentioned below to calculate ET.

From the Penman-Monteith equation, the FAO derived a method to compute reference ET. In this method, the reference vegetation is defined as a hypothetical vegetation with an assumed height of 12 cm, a canopy resistance of 70 s/m, and an **albedo** of 0.23, similar to an extensive surface of green grass of uniform height that is actively growing and that has an adequate water supply (Allen and others, 1998). For this type of vegetation, ET can be estimated as

$$ET_o = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T+273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where

ET_o = reference evapotranspiration [mm/d]

u_2 = wind speed at 2 m height [m/s]

(Definitions of other variables are provided above.)

The FAO reference-ET method requires climatological data for solar radiation, air temperature, humidity, and wind speed. Once ET_o is calculated, a crop coefficient, K_c, is used to convert reference ET to crop ET, Et_c, such that $Et_c = K_c * ET_o$. The FAO publishes a number of crop coefficients; Table 4 shows a subset of these coefficients that pertains most closely to wetland environments.

For more information on both the Penman-Monteith equation and the reference-ET equation, refer to the FAO Irrigation and Drainage Paper 56 (Allen and others, 1998), which can be accessed online at http://www.fao.org/docrep/x0490e/x0490e00.htm. This document provides a comprehensive overview of ET and the variables that affect it, as well as factors that might affect the calculation. In addition, it contains a complete list of crop coefficients, and provides alternative methods for calculating reference ET when certain variables are missing.

The Priestley-Taylor (1972) equation, a simplified form of the Penman-Monteith equation, is a radiation-based formula for computing ET. The Priestley-Taylor method assumes atmospheric saturation and does not require collection of relative-humidity or wind-speed data, as expressed in the equation (Sumner, 1996; Priestley and Taylor, 1972):

$$\lambda E = \alpha \frac{\Delta (R_n - G)}{\Delta + \gamma}$$

where

α = Priestley-Taylor coefficient

R_n = net radiation at the crop surface [MJ/m^{2}d]

G = soil heat flux density [MJ/m^2d]

Δ = slope vapor pressure curve [kPa/°C]

γ = psychrometric constant [kPa/°C].

The coefficient, α, is applied as a correction factor to account for the fact that the atmosphere does not usually reach saturation. Over large areas of uniform wet surface, α approaches 1, but for other surfaces it varies; the average value of α was estimated to be 1.26. In a study in which the suitability of various methods used to estimate ET was evaluated, Sumner (1996) found the modified Priestley-Taylor equation to be preferable to Penman-Monteith equation because the modified Priestley-Taylor equation was less demanding in terms of data collection and calculation, but produced equally, if not more, reliable results in his study area.

Other radiation-based methods for estimating ET include the Turc (1961) method, which requires mean daily temperature, solar radiation, and mean daily humidity data, and the Makkink (1957) equation, which requires mean daily temperature and solar radiation data (Lu and others, 2005). A recent study conducted by Lu and others (2005) compares the results of a number of the above-mentioned temperature- and radiation-based methods for determining ET in the southeastern United States.

Data Sources

In New Jersey, pan evaporation data currently are collected at a single weather station in New Brunswick (Figure 20). Evaporation data for this station are available through the National Climatic Data Center (NCDC). In addition, the South Jersey Resource Conservation and Development Council (SJRC&D) hosts a network of 20 weather stations throughout southern New Jersey (Figure 20) for which ET based on local crop content is calculated daily using the

Penman-Monteith equation. Information about each site is found in Table 1-4 (Appendix 1). These data are available by subscription at www.sjrcd.org/index.html.

In addition to these stations for which ET data are available without further calculation, there are also several stations throughout the State for which meteorological data are collected. Depending on the specific parameters measured, these data can be inputted into one of the ET equations mentioned above. For example, daily temperature data are available through the NCDC and can be used in any of the temperature-based methods. Also, radiation data is available in the National Solar Radiation Database at http://rredc.nrel.gov/solar/old_data/nsrdb/.

Water-Budget Steps

The steps used to quantify the ET portion of a wetland water budget are outlined in Figure 21. As for the precipitation component, daily values from an ET data-collection station that most closely represents the mitigation site should be obtained, if possible. Once a representative station has been identified, the period of record must be examined and data from representative wet, dry, and average precipitation years must be obtained. However, because of the scarcity of ET data-collection stations, it is likely that daily ET values will have to be estimated through the use of direct-measurement techniques or meteorological methods. If a temperature-based meteorological method is used, much of the temperature input data can be obtained from a representative weather station. Once daily and monthly ET values have been obtained, measured, or estimated for representative wet, dry, and average precipitation years, they can be graphed along with the other components of the water budget.

Change in Storage

As mentioned earlier, the change in storage in a wetland is the difference between water inflow to, and outflow from, the wetland for any given period of time. If the water-budget calculation results in a negative value for change in storage, then more water is flowing out of the wetland than into it. Conversely, a positive change in storage reflects an overall net flow of water into the wetland system (Carter, 1996). Wetlands develop at locations where there is a seasonally recurring period during which water inputs exceed water outputs (Tiner, 2005).

Change in storage can be calculated directly (post-construction, or in a reference wetland site) if appropriate water-level data are available. For the standing-water portion of a wetland, change in storage (in units of depth) is equal to the change in water level. To convert this value to a volume, multiply the change in water level by the area affected. A stage gage can be used to help measure change in storage for the standing-water portion. For the portion of the wetland system contained in unconfined saturated sediments, change in storage is equal to the change in water level multiplied by the specific yield of the sediment (Freeze and Cherry, 1979). Sediments that consist primarily of sand particles typically have a higher specific yield than those made up of silt and clay; pore spaces are larger in sands, which consequently have a smaller specific retention than silt and clay (Fetter, 2001). By calculating change in storage using one or both of these data-based methods, the change-in-storage term serves as a check of the water balance.

Frequently, however, storage (and uncertainty due to measurement) represents a residual term of the water budget and, as such, can be viewed as a predictive term. One problem with estimating storage as a residual term is that it will include the accumulated error associated with each of the other components of the water budget. If the change in storage is calculated based on water-level measurements in a reference wetland, as discussed above, then the magnitude of the net accumulated error can be estimated. Uncertainty and error associated with the water budget are addressed below.

Uncertainty/Errors

As stated in Healy and others (2007), "all water-budget calculations contain some uncertainty. There are two general sources of this uncertainty: natural variability of the hydrologic cycle and errors associated with measurement technique." Uncertainties in daily water budgets generally are greater than uncertainties in water budgets calculated for longer time periods--weekly, monthly, or yearly. Even in an ideal situation with unlimited resources and where state-of-the-art methods are used, uncertainties are inherent in water-budget estimates, and real-world application of practical water-budget methodologies for wetland mitigation sites will provide approximate results.

Although uncertainty can not be eliminated, it can be reduced with the use of appropriate methods and/or accounted for. For example, examining the water budget for representative wet, dry, and average years helps to account for some of the natural variability associated with the hydrologic cycle; if a proposed site can be expected to function as a wetland under such a range of conditions, confidence that the site will succeed is high. Commonly, various assumptions are made during the development of wetland water budgets, and one or more of the estimates of inputs and outputs may be made by using direct-measurement techniques with inherent associated levels of error or as a residual of the water-budget equation. Potential differences in water balances that result from the application of assumptions and techniques used in estimating precipitation, runoff, and evaporation are discussed by Winter (1981).

The uncertainty associated with these assumptions and estimations can be accounted for by conducting a sensitivity analysis to show how changes in the magnitude of an individual component, or a key factor used to estimate the component, affect the overall water budget. A sensitivity analysis is conducted by varying the water-budget input values over a reasonable range that reflects the accuracy of each estimate, and observing the relative change in the overall water budget. A reasonable range for a budget component can be determined by estimating the budget using different methods or data sets. A relatively narrow range of values for a component may indicate greater confidence in its accuracy. If a small change in the value of a parameter (such as hydraulic conductivity) results in a relatively large change in the overall water budget, the budget is said to be sensitive to that parameter. If a sensitivity analysis of a proposed mitigation site's water budget indicates a high sensitivity to a particular parameter or parameters that will likely affect the performance of the wetland design, then the methods used to estimate those parameters may require re-evaluation using additional information, or the design may need to be modified to reduce the sensitivity.

Conclusion

The inflows and outflows of water that make up a freshwater wetland's hydrologic cycle can be accounted for in a water budget. Precipitation, surface-water inflow, and ground-water inflow are the hydrologic inputs to a wetland system; ET, surface-water outflow, and ground-water outflow are the hydrologic outputs. The magnitude of each component of the water-budget equation should be computed using a combination of data sources, data-collection methods, and numerical-modeling techniques. By facilitating the assessment of the variability and relative importance of the individual components, a water budget serves as a valuable tool in understanding the hydrologic processes that take place in a wetland.

If the guidelines presented in this manual are followed, the final calculated water-budget values should provide an indication of the projected hydroperiod for a wetland mitigation site under wet, dry, and average precipitation conditions. A graphical representation of the water-budget components can be a useful visual representation of predicted hydroperiods for wetland mitigation sites. An example of a water budget for a hypothetical wetland mitigation site in New Jersey is presented that outlines some of the typical steps involved in creating a wetland water budget based on data sources and data methods presented in this manual. The example also shows readers how water-budget computations can be translated into graphical representations that clearly indicate the estimated hydroperiod under a range of conditions. A sensitivity analysis helps in evaluating the consequences of uncertainties. A mitigation site must have adequate water (the amount depends on the goals and objectives of the wetland mitigation site) during parts of the year, especially during the growing season. Resultant daily water levels should indicate saturated conditions at the surface for a sufficient period of time during the growing season to support intended wetland functions and values.

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Glossary

The source of each definition is shown at the end of the glossary in the footnote associated with each entry.

Albedo[2]**--**The fraction of solar radiation reflected by the Earth's surface.

Alluvial swamp[3]--A forested floodplain wetland with soil consisting generally of fine-grained sediments that have been deposited by overbank transport of sediments from a stream.

Aquifer[4]--A geologic formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield significant quantities of water to springs and wells.

Bog[5]**--**A peat-accumulating wetland that has no significant inflows or outflows and supports acidophilic mosses, particularly *Sphagnum.*

Capillary fringe[6]--A zone immediately above the water table (zero gauge pressure) in which water is drawn upward from the water table by capillary action.

Channelized flow[3]--Flow that is confined to a channel (in contrast to non-channelized flow or overland flow).

Confined aquifer[7]--An aquifer that is bounded above and below by sediments or rocks of lower permeability (confining unit).

Confining layer[4]--A body of impermeable or distinctly less permeable (see permeability) material stratigraphically adjacent to one or more aquifers that restricts the movement of water into and out of the aquifers.

Creation[8]--The establishment of freshwater wetland or State open water characteristics and functions in uplands.

Delegable waters[8]--All waters of the United States, as defined in this section, within New Jersey, except waters which are presently used, or are susceptible to use in their natural condition or by reasonable improvement, as a means to transport interstate or foreign commerce, shoreward to their ordinary high water mark. This term includes all waters which are subject to the ebb and flow of the tide, shoreward to their mean high water mark, including wetlands that are partially or entirely located within 1000 feet of their ordinary high water mark or mean high tide.

Waters that are not delegable waters include, but are not limited to:

1. The entire length of the Delaware River within the State of New Jersey;
2. Waters of the United States under the jurisdiction of the Hackensack Meadowlands Development Commission; and
3. Greenwood Lake.

Discharge[4]--The volume of fluid passing a point per unit of time, commonly expressed in cubic feet per second, million gallons per day, gallons per minute.

Enhancement[8]--The improvement of the ability of an existing, degraded wetland or State open water to support natural aquatic life, through substantial alterations to the soils, vegetation, and/or hydrology.

Estuarine[5]--Pertaining to an estuary (general location where a river meets the ocean and freshwater mixes with saltwater).

Evapotranspiration[4]--The process by which water is discharged to the atmosphere as a result of evaporation from the soil and surface-water bodies, and transpiration by plants.

Fall Line[4]--Imaginary line marking the boundary between the ancient, resistant crystalline rocks of the Piedmont Province of the Appalachian Mountains, and the younger, softer sediments of the Atlantic Coastal Plain Province in the Eastern United States. Along rivers, this line commonly is reflected by waterfalls.

Hydraulic conductivity[4]--The capacity of a rock to transmit water. It is expressed as the volume of water at the existing kinematic viscosity that will move in unit time under a unit hydraulic gradient through a unit area measured at right angles to the direction of flow.

Hydraulic gradient[4]--The change of hydraulic head per unit of distance in a given direction.

Hydraulic head[4]--The height of the free surface of a body of water above a given point beneath the surface.

Hydrodynamics[5]--An expression of the fluvial energy that drives a system.

Hydrogeomorphology[5]--Combination of climate, basin geomorphology, and hydrology that collectively influences a wetland's function.

Hydrograph[4]--A graph showing variation of water elevation, velocity, streamflow or other property of water with respect to time.

Hydroperiod[5]--The seasonal pattern of the water level of a wetland. This approximates the hydrologic signature of each wetland type.

Hydrophytic vegetation[5]--Plant community dominated by plants adapted to wet conditions.

Infiltration[4]--The downward movement of water from the atmosphere into soil or porous rock.

Lacustrine[5]--Pertaining to lakes or lake shores.

Non-channelized flow[3]--Normally reserved for surface flow that is diffuse and thus not confined to a channel. Also called overland flow and surface runoff.

Non-delegable waters[8]--Waters that are not delegable waters (see delegable waters).

Ombrotrophic[5]--Literally rain fed, referring to wetlands that depend on precipitation as the sole source of water.

Palustrine[5]--Nontidal wetlands.

Perched ground water[4]--Unconfined ground water separated from an underlying main body of ground water by an unsaturated zone.

Permeability[7]--A property of a layer of rock or unconsolidated sediments that determines how easily a fluid, such as water, can move through it. Sands and gravels have high permeabilities; silts and clays have low permeabilities.

Piezometer[5]--Ground-water well that is only partially screened and thus measures the piezometric head of an isolated part of the ground water.

Porosity[7]--The ratio of the volume of open (void) spaces in a rock or sediment through which fluid can flow to the total volume of the rock or sediment.

Potential evapotranspiration[4]--The amount of moisture which, if available, would be removed from a given land area by evapotranspiration; expressed in units of water depth.

Reference wetland[5]--Natural wetland used as a reference or control site to judge the condition of another created, restored, or impacted wetland.

Restoration[8]**--**The reestablishment of wetland and/or State open water characteristics and functions in an area that was once a freshwater wetlands and/or State open water but is no longer. For example, an area that has been drained and farmed could be restored to its original condition by blocking or removing drainage devices and replanting with appropriate wetlands plants.

Riparian[5]--Pertaining to the bank of a body of flowing water; the land adjacent to a river or stream, that is, at least periodically, influenced by flooding. A riparian ecosystem has a high water table because of its proximity to an aquatic ecosystem, usually a stream or river.

Specific yield[4]**--**The ratio of the volume of water that will drain under the influence of gravity to the volume of saturated rock.

Unconfined aquifer[7]--An aquifer that is near land surface and is not overlain by a confining unit. Also called a water-table aquifer.

Water table[7]--The upper surface of the saturated zone, below which the openings in the rocks are completely filled with water. At the water table, the water pressure equals atmospheric pressure.

Water year[4]--A continuous 12-month period selected to present data relative to hydrologic or meteorological phenomena during which a complete annual hydrologic cycle normally occurs. The water year used by the U.S. Geological Survey runs from October 1 through September 30, and is designated by the calendar year in which it ends.

Wetland function[4]--A process or series of processes that take place within a wetland that are beneficial to the wetland itself, the surrounding ecosystems, and people.

Wetland value[5]--Something worthy, desirable, or useful to humanity. Humans decide what is of "value" in an ecosystem.

Sources of terms and definitions used in this glossary:

[2] Allen and others, 1998

[3] Brinson, 1993

[4] U.S. Geological Survey, 2004

[5] Mitsch and Gosselink, 2000

[6] U.S. Army Corps of Engineers, 1987

[7] Watt, 2000

[8] New Jersey Department of Environmental Protection, 2003

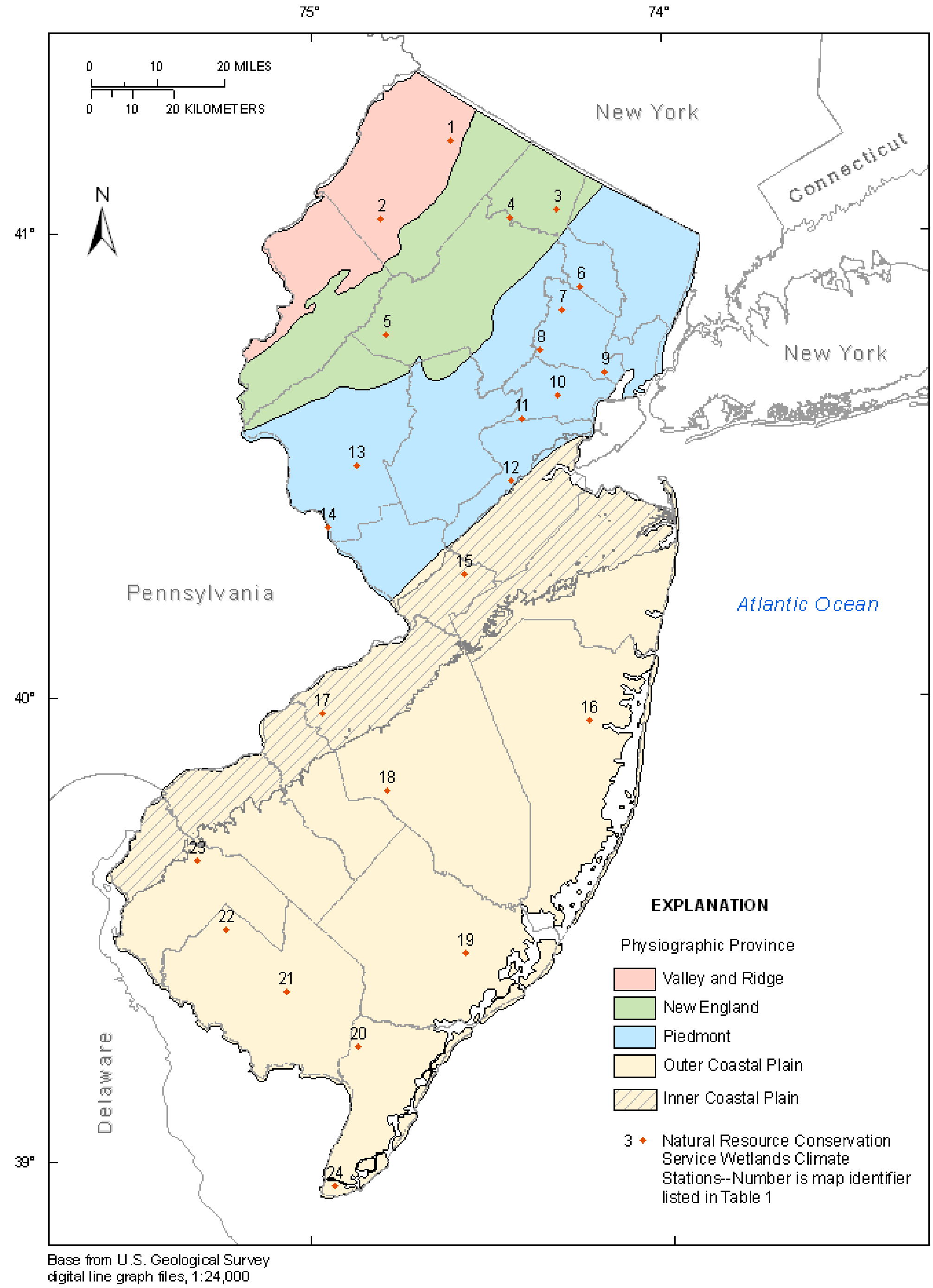


Figure 1. Stations in New Jersey for which growing-season dates are available. Stations are part of the Natural Resource Conservation Service's Wetlands Climate (WETS) network.

Table 1. Selected information for stations in New Jersey that are listed in the Natural Resource Conservation Service's Wetlands Climate (WETS) Table.

[ID, identification number; Station locations are shown in Figure 1]

Map ID	Station name	Station ID	Growing-season beginning and ending dates[1]	Length of growing season (number of days)
1	Sussex 1 SE	NJ8644	4/20 to 10/21	184
2	Newton St Pauls Abbey	NJ6177	4/22 to 10/19	180
3	Wanaque Raymond Dam	NJ9187	4/ 2 to 11/ 8	221
4	Charlotteburg Reservoir	NJ1582	4/14 to 10/21	190
5	Long Valley	NJ5003	4/16 to 10/21	188
6	Little Falls	NJ4887	4/ 2 to 11/ 6	218
7	Essex Fells Serv Bldg	NJ2768	4/ 7 to 11/ 4	210
8	Canoe Brook	NJ1335	4/ 8 to 10/29	204
9	Newark WSO AP	NJ6026	3/20 to 11/26	252
10	Cranford	NJ2023	4/11 to 10/31	203
11	Plainfield	NJ7079	4/ 1 to 10/30	213
12	New Brunswick 3 SE	NJ6055	3/31 to 11/ 5	220
13	Flemington	NJ3029	4/10 to 10/29	203
14	Lambertville	NJ4635	4/ 7 to 10/28	204
15	Hightstown 2 W	NJ3951	4/ 6 to 11/ 1	209
16	Toms River	NJ8816	4/10 to 11/ 3	207
17	Moorestown	NJ5728	4/ 4 to 11/ 4	214
18	Indian Mills 2 W	NJ4229	4/15 to 10/27	195
19	Atlantic City WSO AP	NJ0311	4/ 6 to 11/ 3	212
20	Belleplain Sta Forest	NJ0690	4/13 to 10/29	199
21	Millville FAA Airport	NJ5581	3/30 to 11/ 7	222
22	Seabrook Farms	NJ7936	3/22 to 11/14	236
23	Woodstown	NJ9910	3/30 to 11/ 8	223
24	Cape May 2 NW	NJ1351	3/20 to 11/24	249

[1] There is a 70 percent chance that the growing season will occur between the beginning and ending dates shown. Dates are based on a threshold surface temperature of 28 °F for the last killing frost in the spring and the first killing frost in the fall. For additional probability and threshold surface temperature scenarios, refer to the complete WETS Table (http://www.wcc.nrcs.usda.gov/cgibin/getwetst.pl?state=New+Jersey).

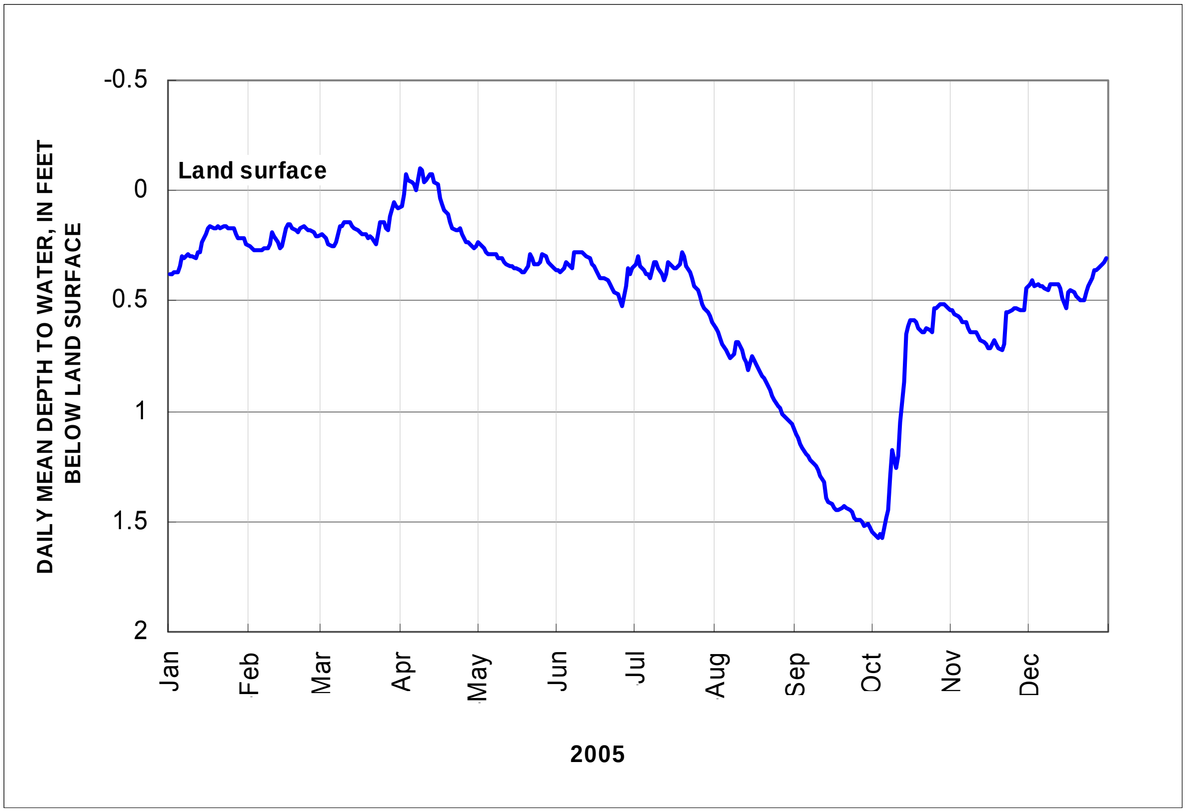


Figure 2. Hydrograph for a well in a forested wetland in the Pinelands area of southern New Jersey based on continuous data collected in 2005.

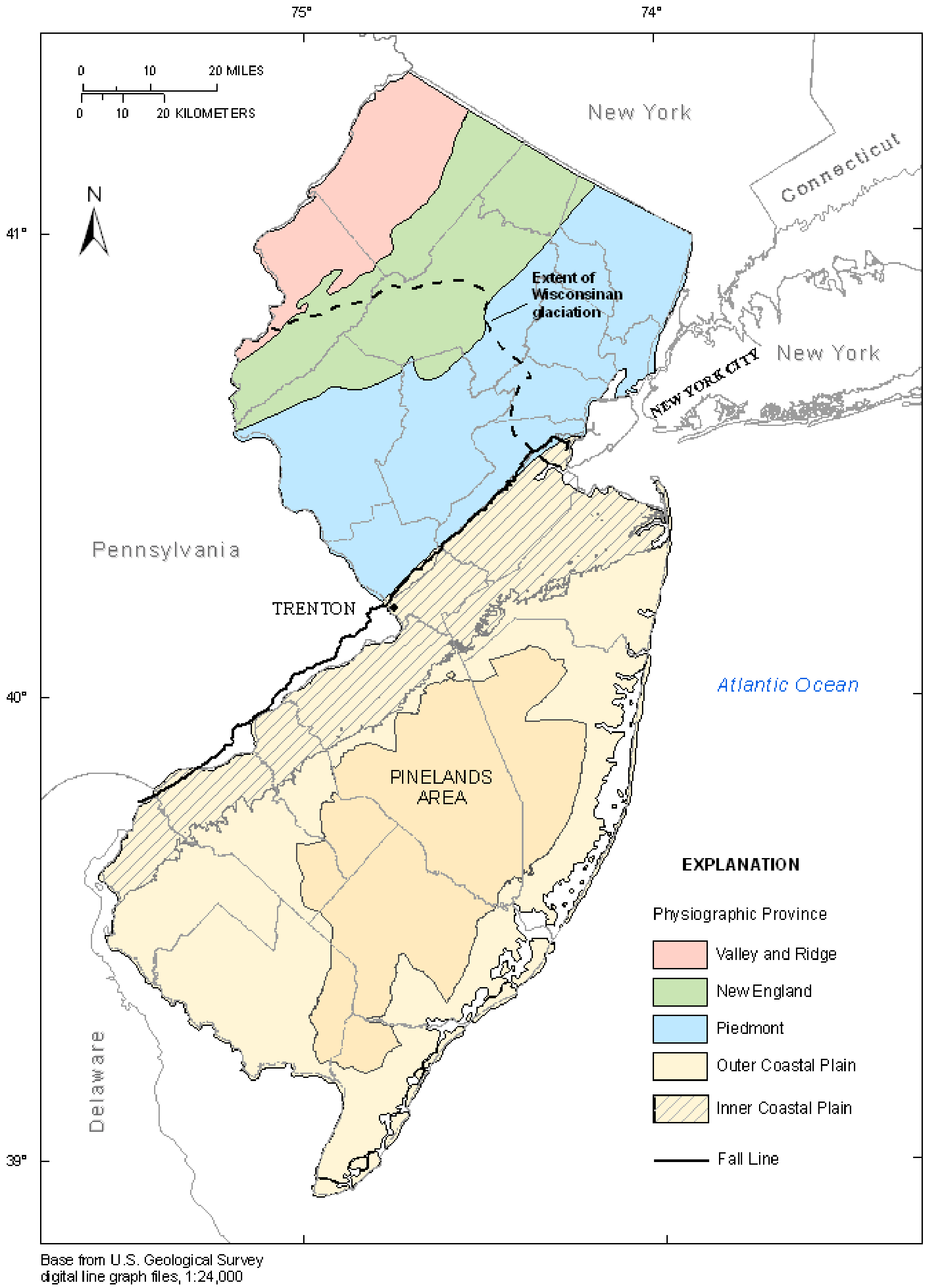


Figure 3. Physiographic provinces of New Jersey. North of the Fall Line, the subsurface is composed of glacial valley-fill deposits, fractured shale, limestone, sandstone, conglomerate, and crystalline-rock units; south of the Fall Line, the subsurface consists of unconsolidated gravels, sands, silts, and clays.

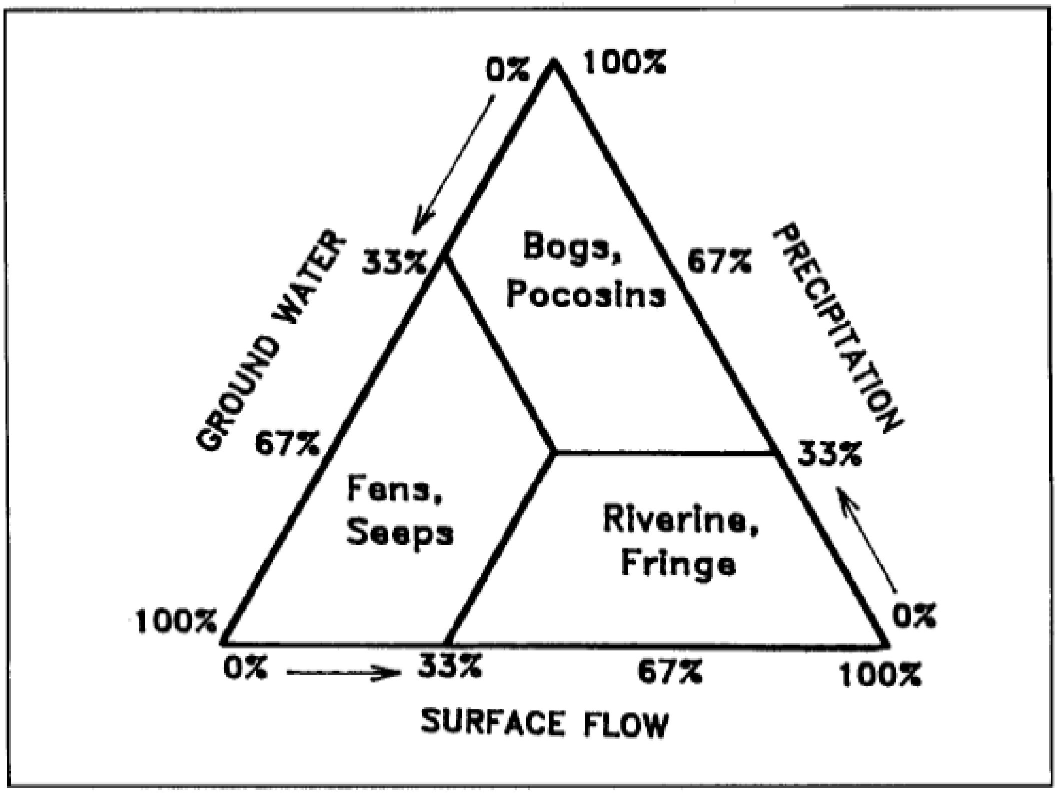


Figure 4. The relative contribution of each water source to major wetland types, based on the Hydrogeomorphic Approach. (From Brinson, 1987)

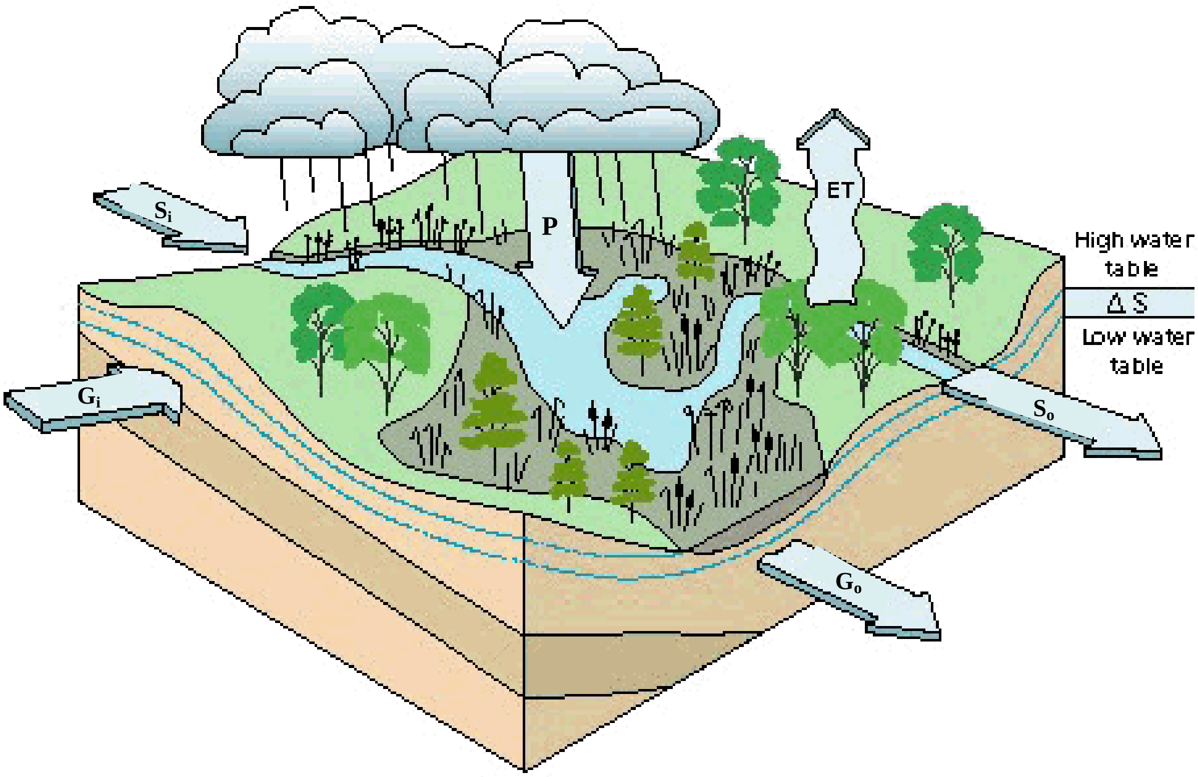


Figure 5. The components of the wetland water budget, where ΔS = change in volume of water storage in a defined area over time, P = precipitation, S_i = surface-water inflow, G_i = ground-water inflow, ET = evapotranspiration, S_o = surface-water outflow, and G_o = ground-water outflow. (Modified from Carter, 1996)

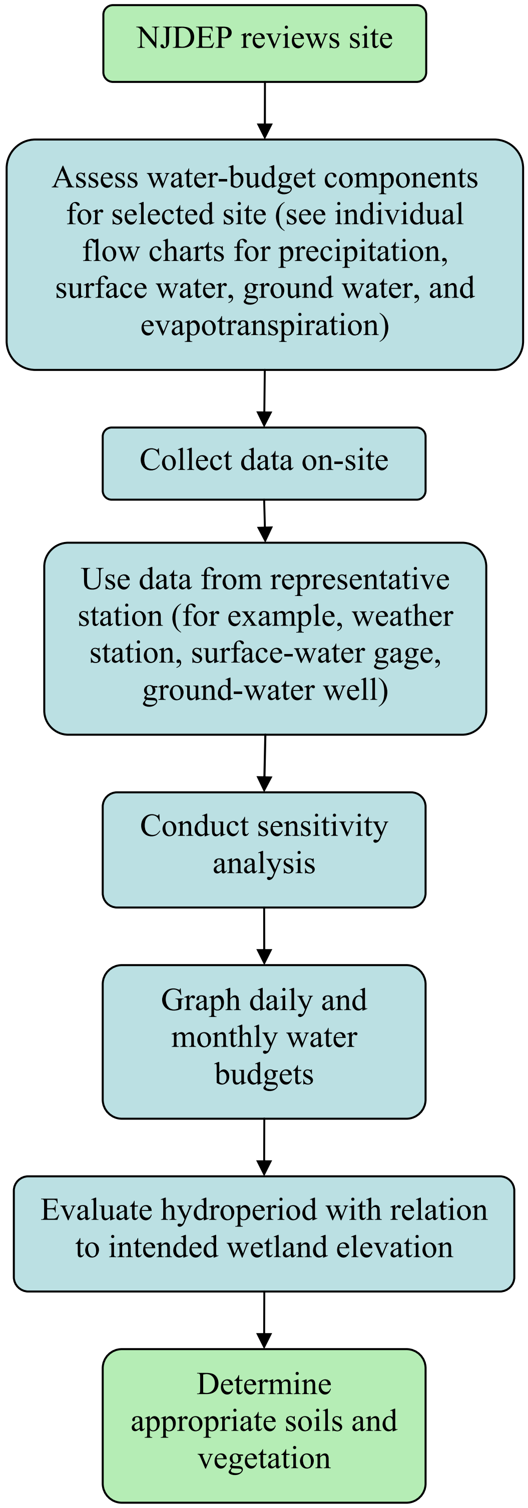
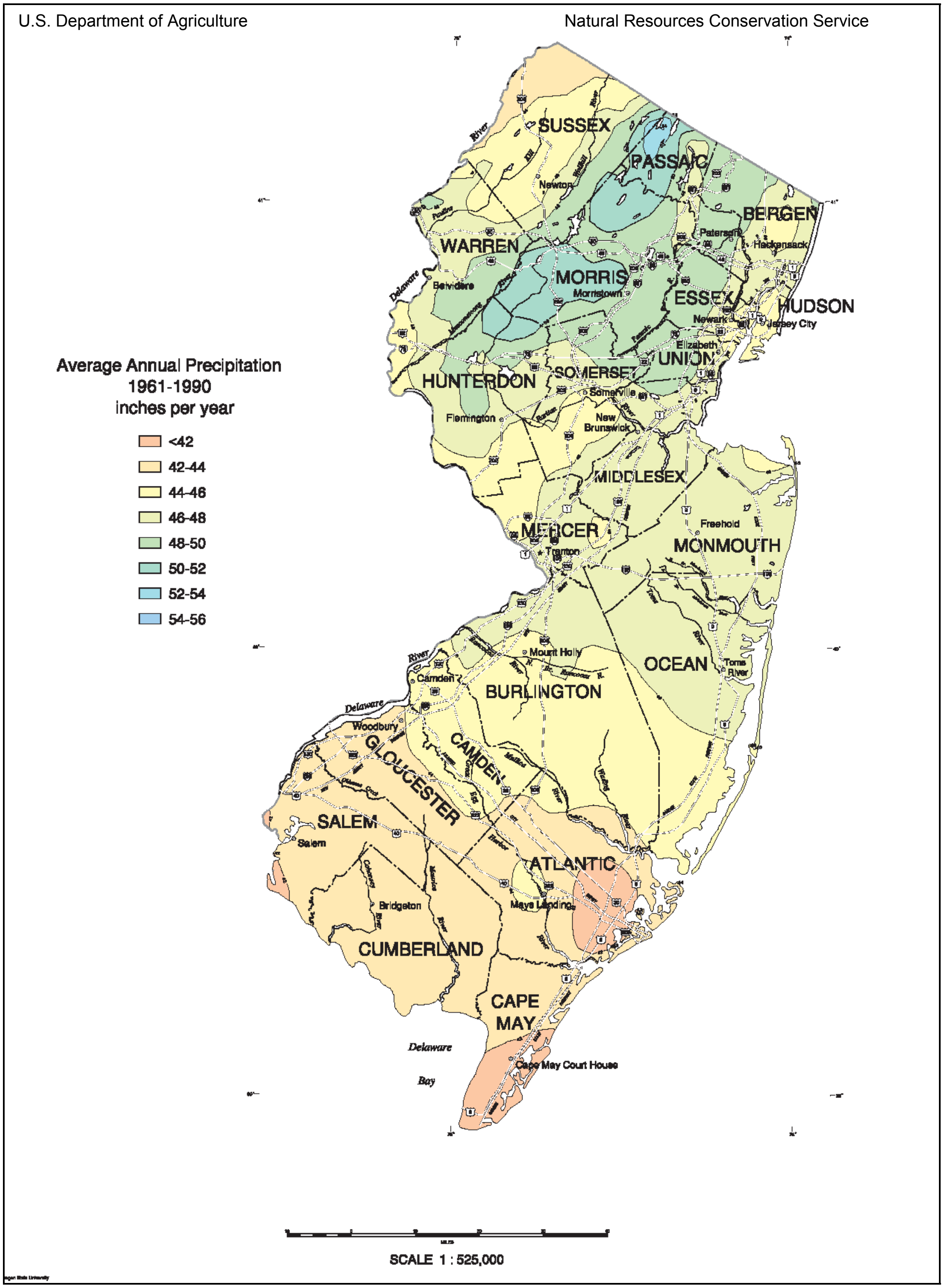


Figure 6. Flow chart showing the general steps necessary to complete a water budget for a wetland mitigation site in New Jersey. [NJDEP, New Jersey Department of Environmental Protection; blue polygons represent water-budget steps, green polygons represent additional mitigation activities]

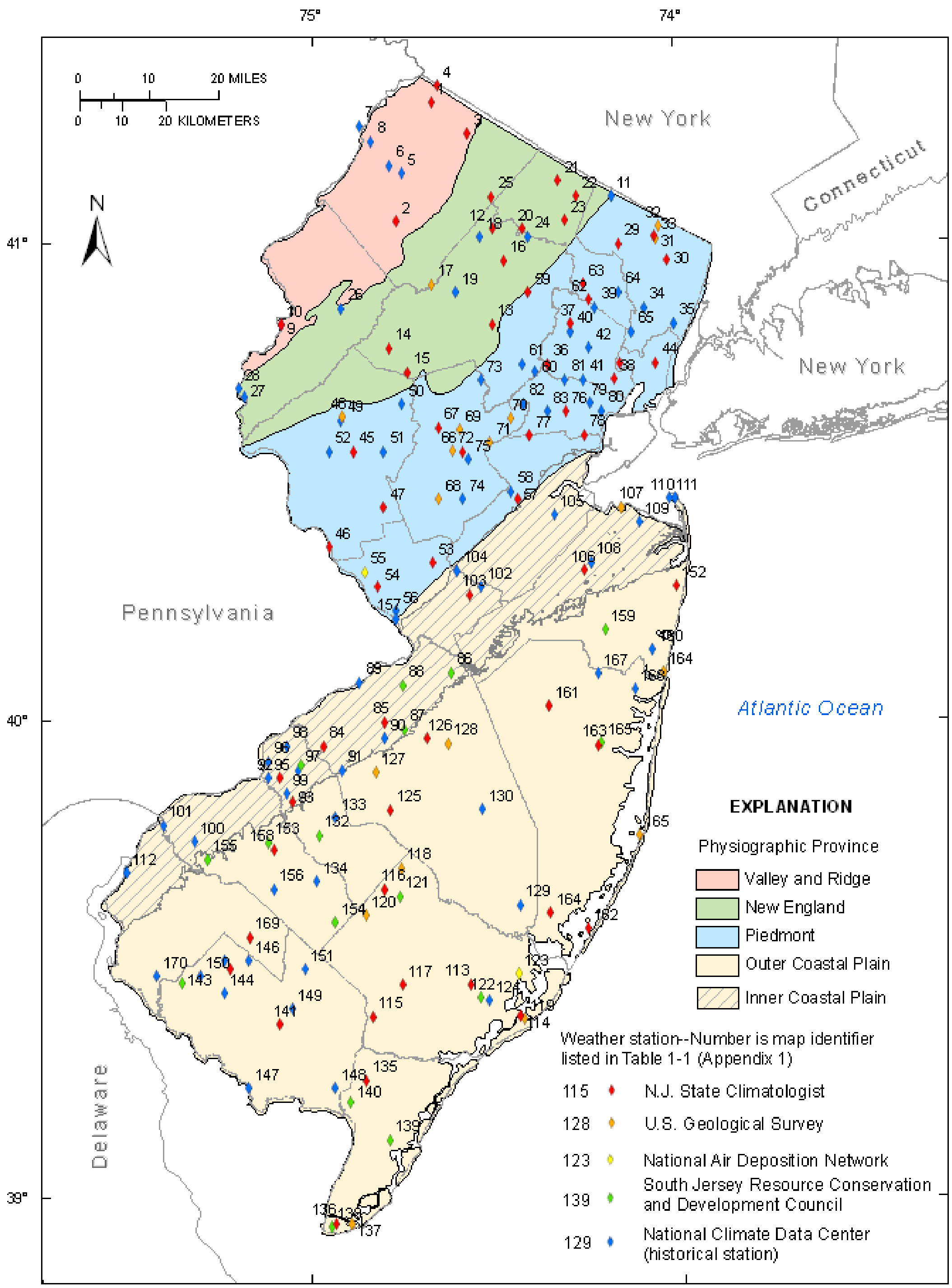


Base from USDA NRCS National Cartography and Geospatial Center, Fort Worth, TX 1998

Figure 7. Average annual precipitation for New Jersey, 1961-90. (From Natural Resources Conservation Service, 1998)

Table 2. Average annual precipitation for New Jersey, 1895-2001. (From Watson and others, 2005)

Climate region	Average annual precipitation, in inches		
	1895-2001	1895-1970	1971-2001
Northern (Piedmont, New England, and Valley and Ridge)	46.1	44.6	49.8
Southern (Coastal Plain)	44.2	43.7	45.96



Base from U.S. Geological Survey
digital line graph files, 1:24,000

Figure 8. Weather stations in New Jersey. Information collected at weather stations includes precipitation, air temperature, soil temperature, and evaporation.

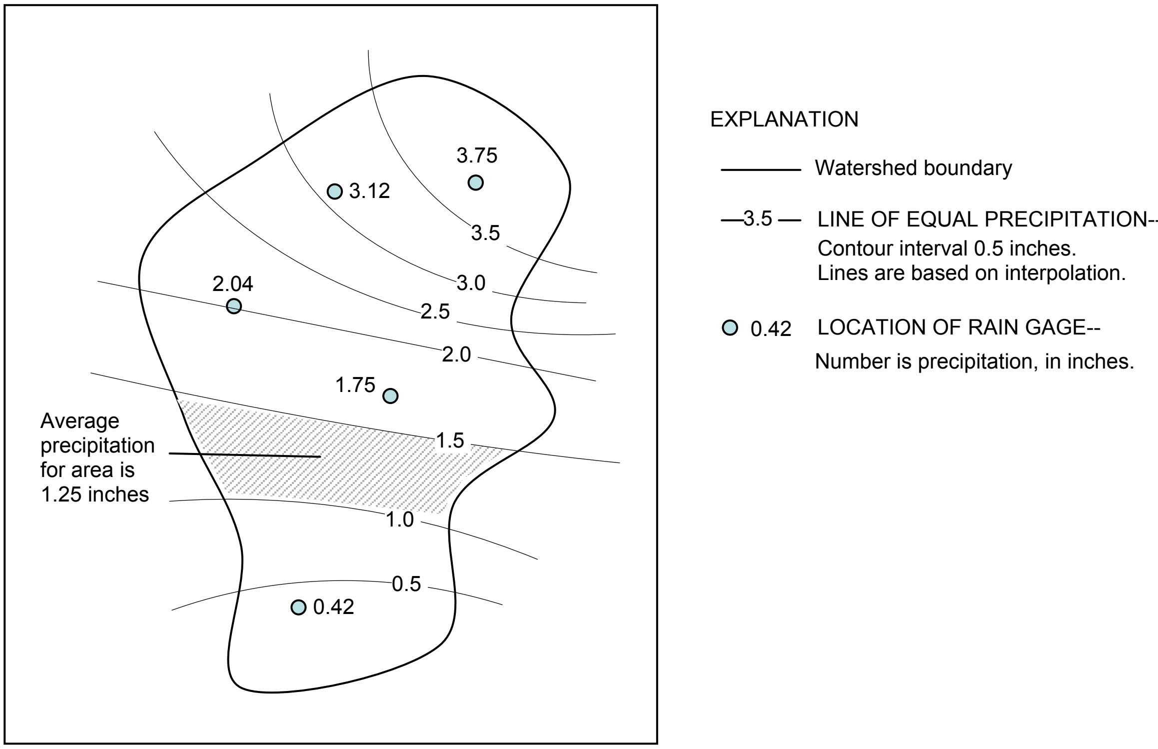


Figure 9. Example isohyetal lines (lines of equal precipitation) for a hypothetical rain-gage network.

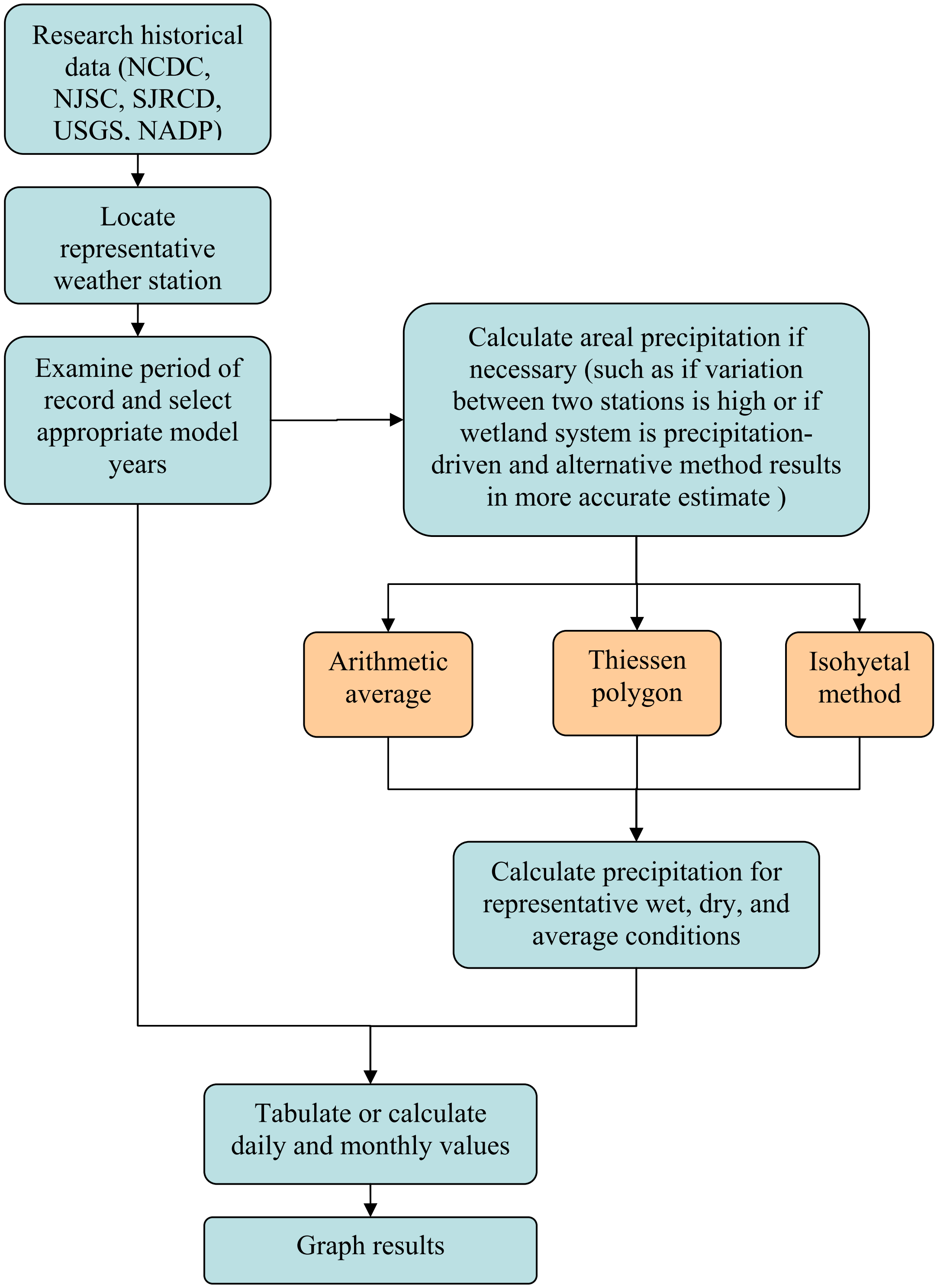


Figure 10. Flow chart for the calculation of the precipitation component of a wetland water budget. [NCDC, National Climatic Data Center; NJSC, New Jersey State Climatologist; SJRCD, South Jersey Resource Conservation and Development; USGS, U.S. Geological Survey; NADP, National Air Deposition Program; blue polygons represent steps, orange polygons represent methods]

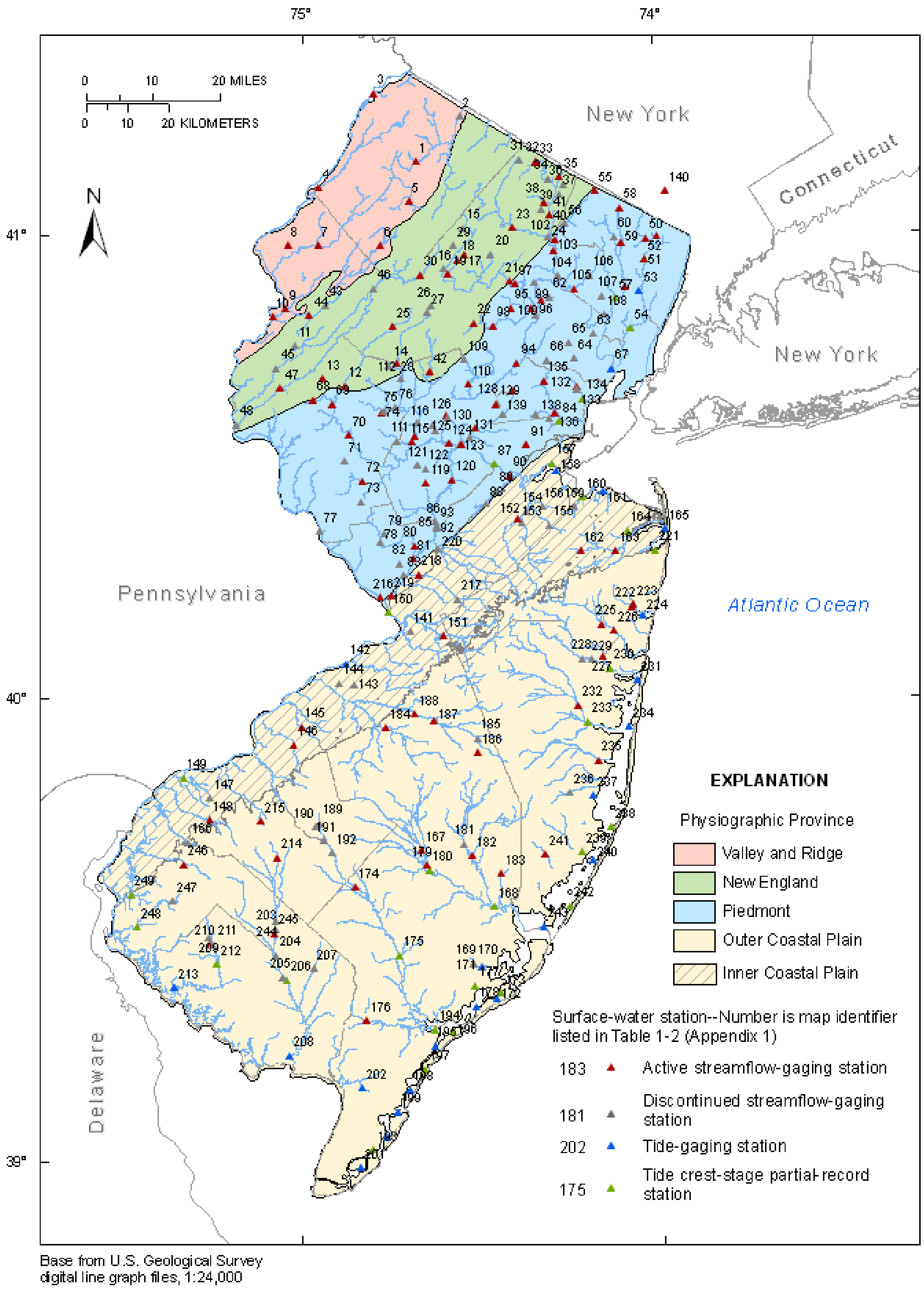


Figure 11. Streamflow-gaging stations, tide-gaging stations, and crest-stage partial-record stations active in New Jersey in water year 2006. Stream stage is measured continuously at the streamflow-gaging stations. At discontinued stations, data are no longer collected, but historical records are maintained by the U.S. Geological Survey. Tide gages measure the highs and lows of the tide. Crest-stage partial-record stations record the highest flow during a specific period.

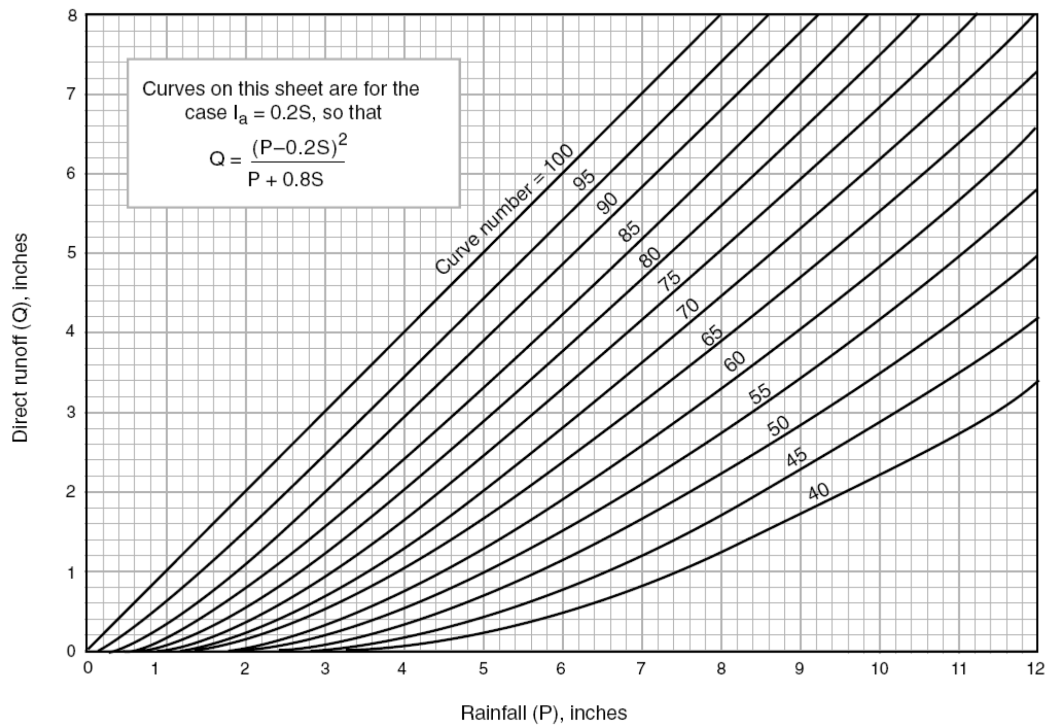


Figure 12. Solution of runoff equation, where I_a = initial abstraction, S = potential maximum retention after runoff begins. (From U.S. Department of Agriculture, 1986)

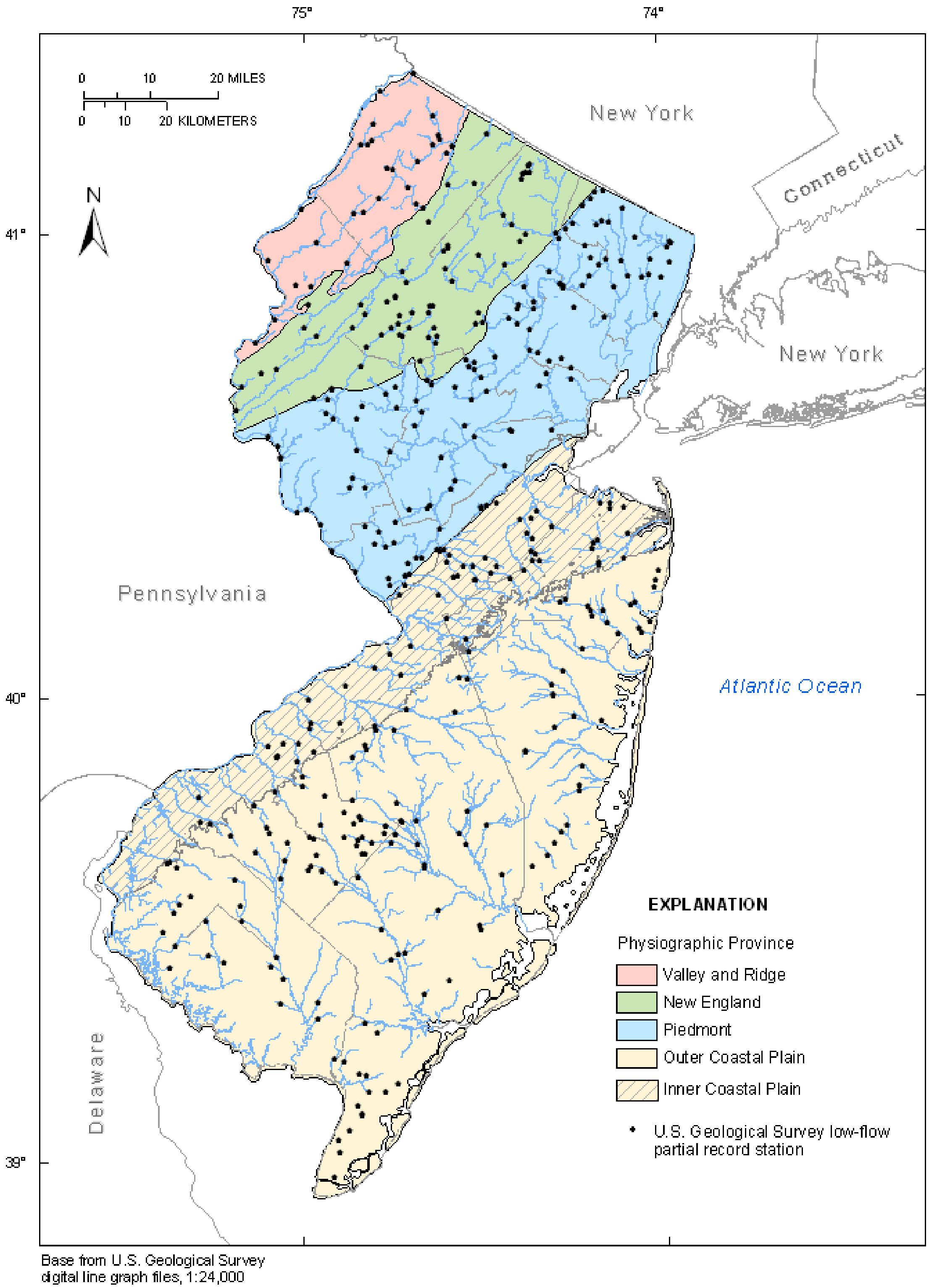


Figure 13. Low-flow partial-record stations in New Jersey through 2007. Each year streamflow is measured at a subset of low-flow partial-record stations under base-flow conditions.

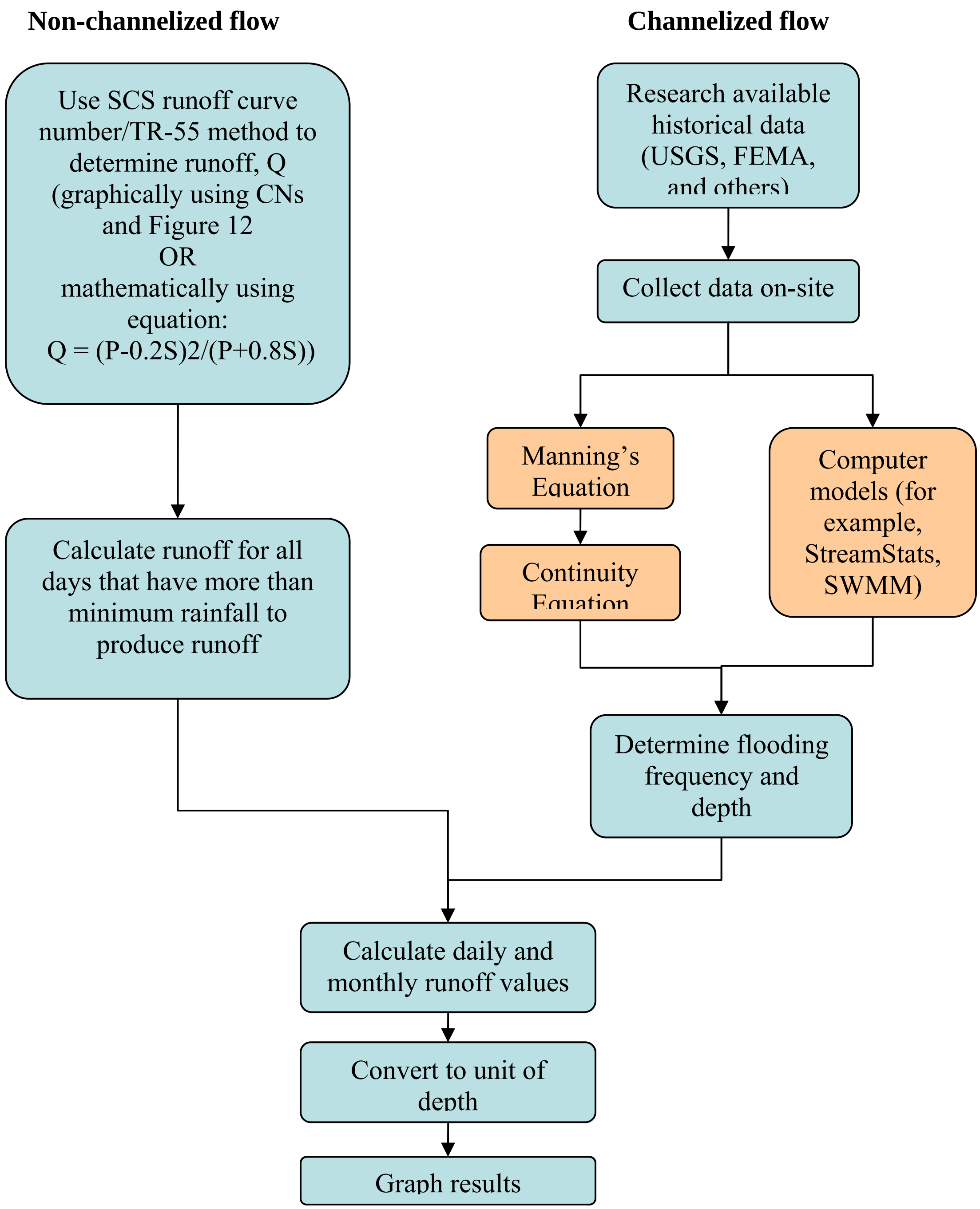


Figure 14. Flow chart for the calculation of the surface-water component of a wetland water budget. [SCS, Soil Conservation Service; USGS, U.S. Geological Survey; FEMA, Federal Emergency Management Agency; CN, curve number; P, precipitation; S, potential maximum retention after runoff begins; SWMM, Storm Water Management Model; blue polygons represent steps, orange polygons represent methods]

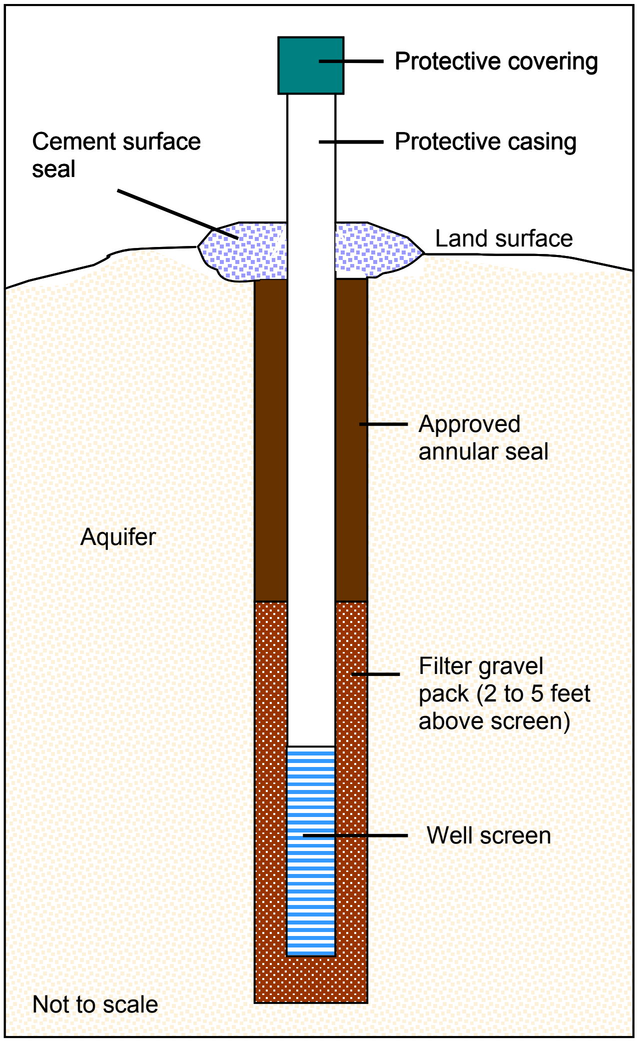


Figure 15. Components of a ground-water well. (Modified from Lapham and others, 1997)

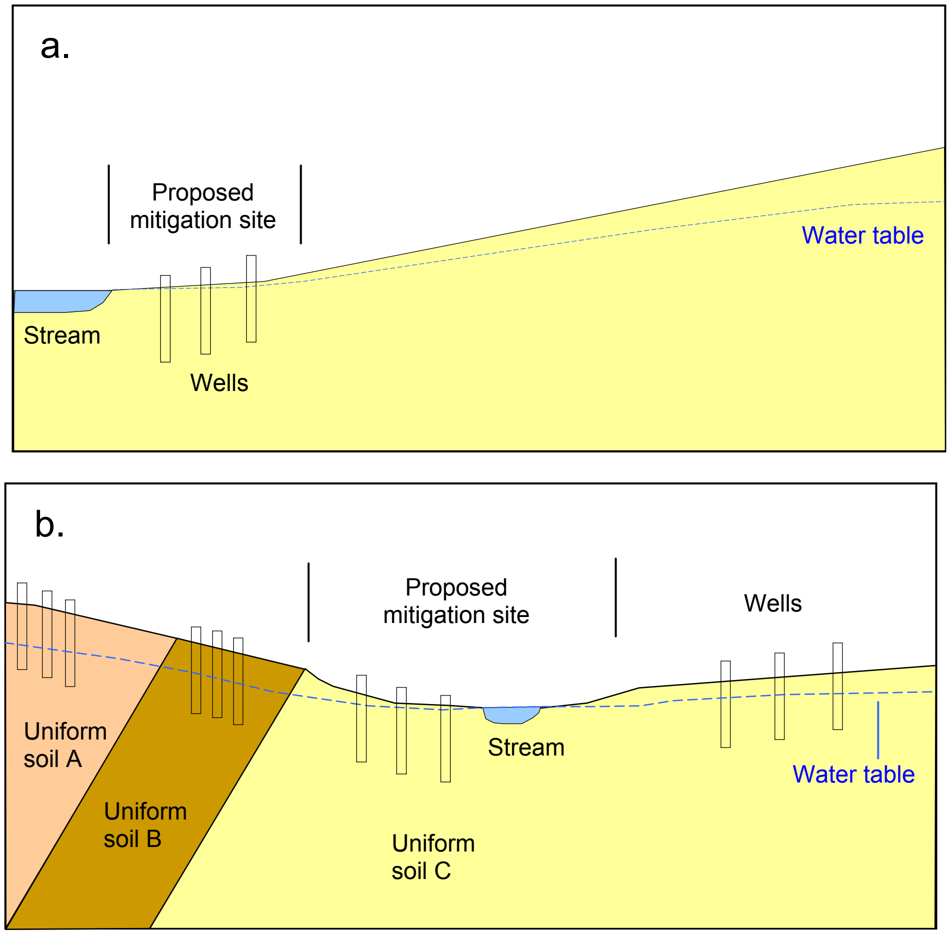


Figure 16. Diagrams showing section of ground-water flow: (a) Simple mitigation site aimed to establish a small riparian corridor that runs along one side of a stream and has only one section of flow; (b) More complex site that encompasses two sides of a stream, each with a different gradient and different soil, for which multiple sets of wells are necessary.

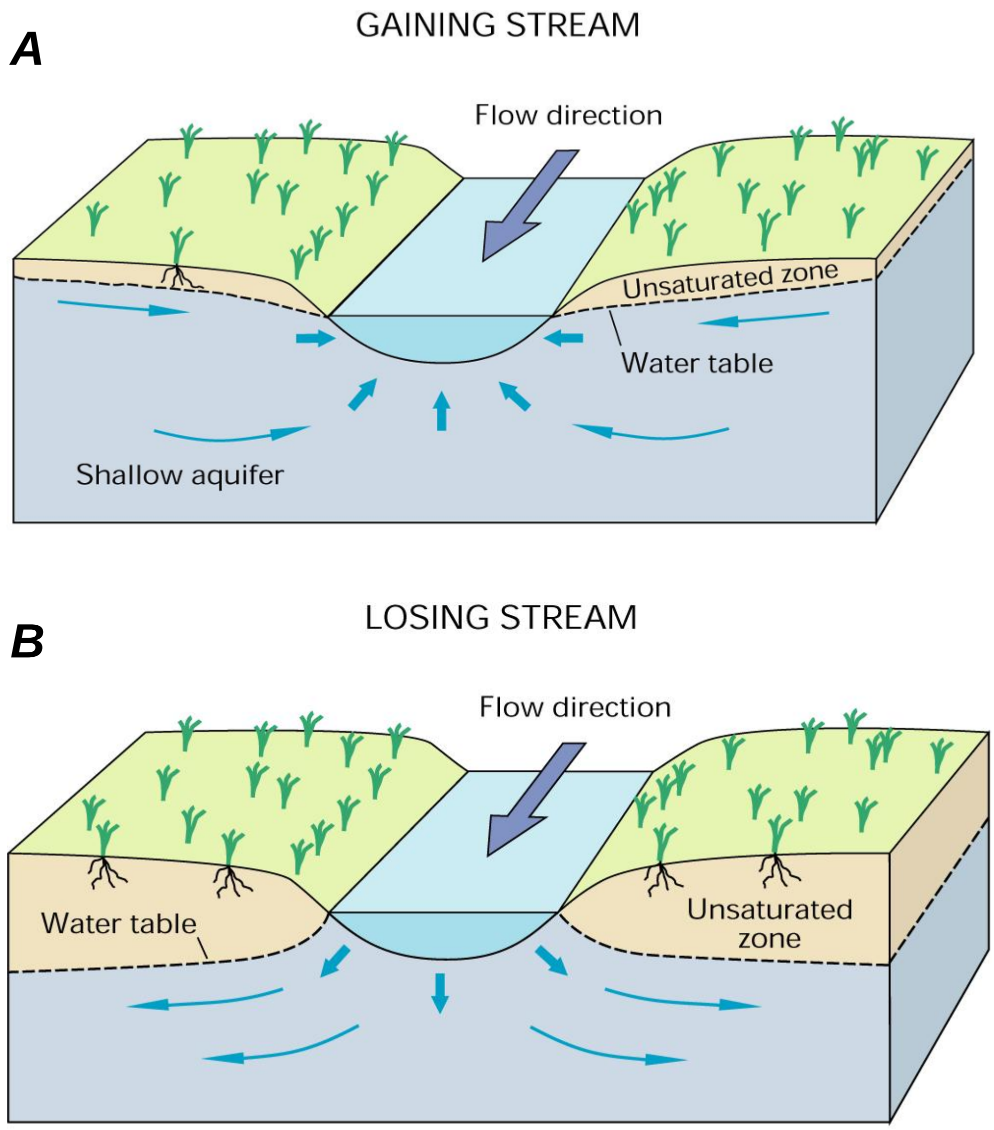


Figure 17. Gaining and losing streams (from Winter and others, 1998). Gaining streams receive water from the ground-water system; losing streams lose water to the ground-water system.

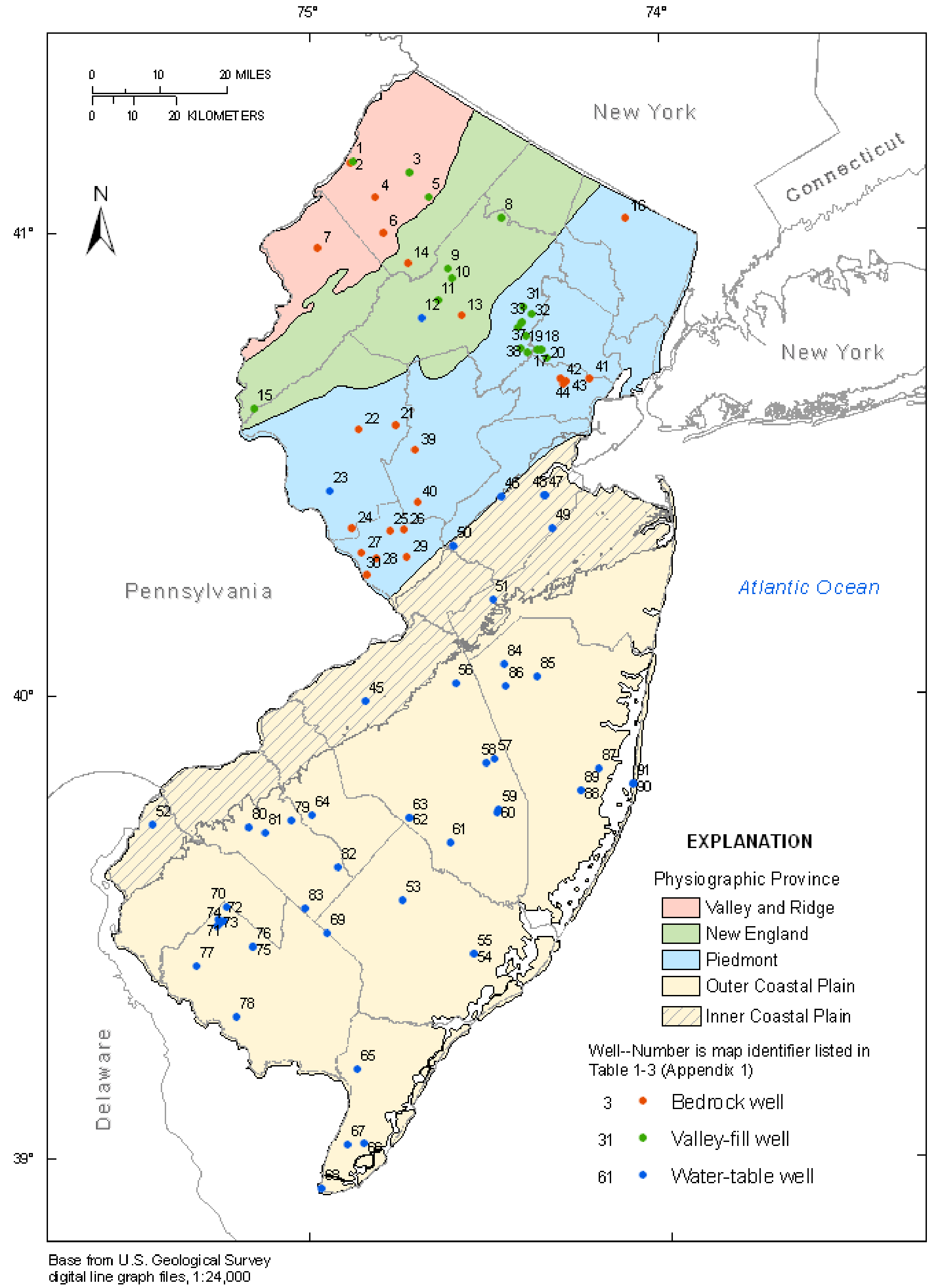


Figure 18. U.S. Geological Survey water-table monitoring wells active in New Jersey in water year 2006. Also shown are wells in bedrock and valley-fill sediments that may show daily water-level fluctuations from precipitation.

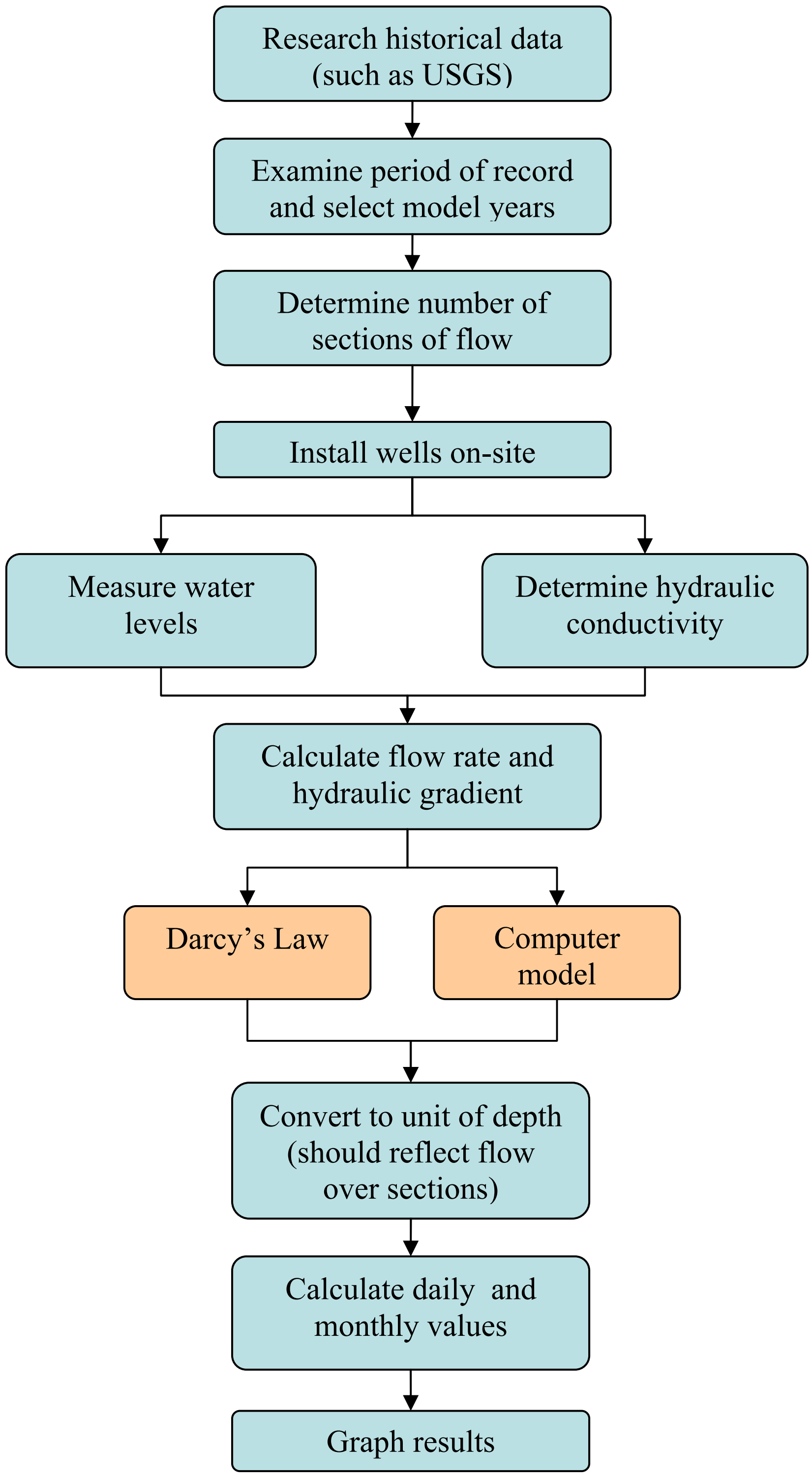


Figure 19. Flow chart for the calculation of the ground-water component of a wetland water budget. [USGS, U.S. Geological Survey; blue polygons represent steps, orange polygons represent methods]

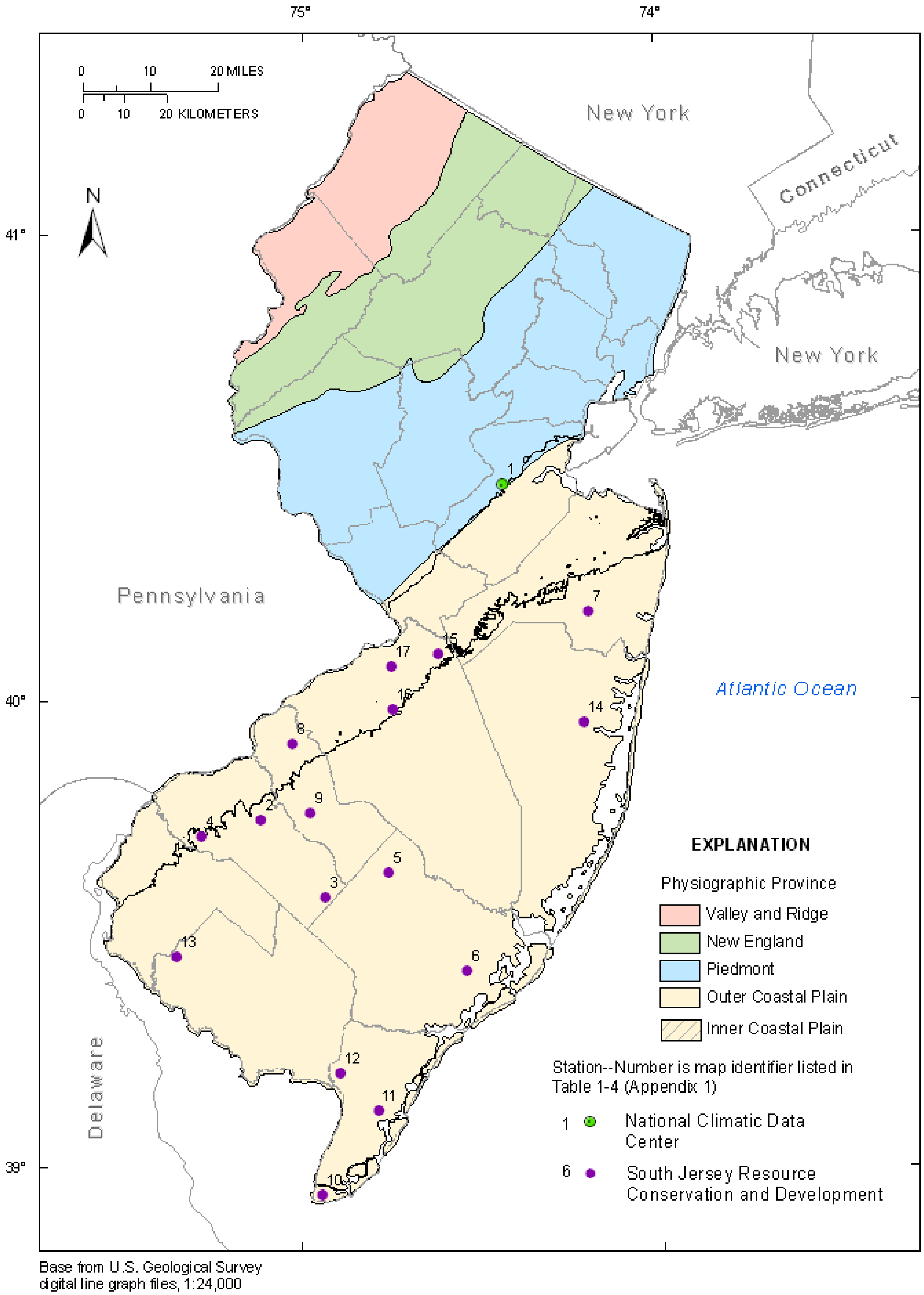


Figure 20. Evapotranspiration data-collection stations active in New Jersey in 2006.

Table 3. Correction factors for monthly sunshine duration. (From Dunne and Leopold, 1978)

Latitude, °	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
60 N	0.54	0.67	0.97	1.19	1.33	1.56	1.55	1.33	1.07	0.84	0.58	0.48
50 N	0.71	0.84	0.98	1.14	1.28	1.36	1.33	1.21	1.06	0.90	0.76	0.68
40 N[1]	0.80	0.89	0.99	1.10	1.20	1.25	1.23	1.15	1.04	0.93	0.83	0.78
30 N	0.87	0.93	1.00	1.07	1.14	1.17	1.16	1.11	1.03	0.96	0.89	0.85
20 N	0.92	0.96	1.00	1.05	1.09	1.11	1.10	1.07	1.02	0.98	0.93	0.91
10 N	0.97	0.98	1.00	1.03	1.05	1.06	1.05	1.04	1.02	0.99	0.97	0.96
0	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

[1] Closest to the latitude of New Jersey

Table 4. Selected single crop coefficients, Kc, and mean maximum plant heights for non-stressed, well-managed crops in subhumid climates (minimum relative humidity >> 45%, wind speed (u_2) >> 2 m/s) for use with the Food and Agricultural Organization (FAO) Penman-Monteith ET_o. (Modified from Allen and others, 1998)

[ET_o, reference evapotranspiration; ini, initial stage of growing period; mid, mid-season stage of growing period; end, end of late stage of growing period; m, meters; --, not applicable]

Crop	$K_{c\ ini}$	$K_{c\ mid}$	$K_{c\ end}$	Maximum crop height (m)
Cattails, bulrushes, killing frost	0.3	1.2	0.3	2
Cattails, bulrushes, no frost	0.6	1.2	0.6	2
Short vegetation, no frost	1.05	1.1	1.1	0.3
Reed swamp, standing water	1	1.2	1	1-3
Reed swamp, moist soil	0.9	1.2	0.7	1-3
Open water, <2 m depth or in subhumid climates or tropics	--	1.05	1.05	--
Open water, >5 m depth, clear of turbidity, temperate climate	--	0.6525	1.2525	--

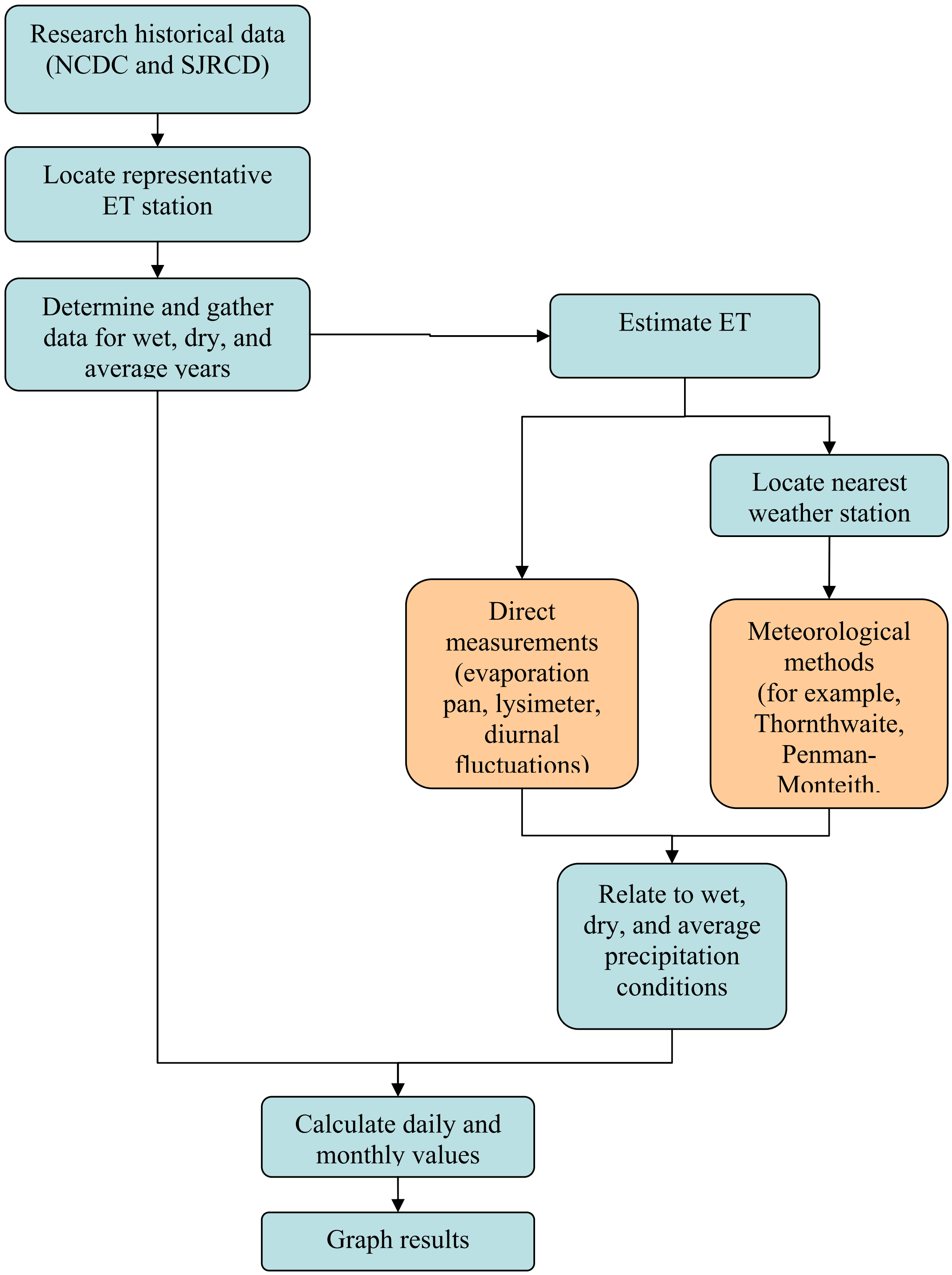


Figure 21. Flow chart for the calculation of the evapotranspiration component of a wetland water budget. [NCDC, National Climatic Data Center; SJRCD, South Jersey Resource Conservation and Development; blue polygons represent steps, orange polygons represent methods]

Appendix 1. Index of selected data-collection stations in New Jersey.

Table 1-1. Selected information for weather stations in New Jersey.

[ID, identification number; NJSC, New Jersey State Climatologist; NCDC, National Climatic Data Center; USGS, U.S. Geological Survey; NADP, National Air Deposition Program; SJRCD, South Jersey Resource and Conservation Development; present, 2007; --, not available; station locations shown in Figure 8]

Map ID	Station name	Station ID	County	Period of record	Source agency
	VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCE				
1	High Point Park	283935	Sussex	1956-2004	NJSC
2	Newton	286177	Sussex	1893-2005	NJSC
3	Sussex 2 NE	288644	Sussex	1893-present	NJSC
4	Sussex 8 NNW	288648	Sussex	1992-2004	NJSC
5	Branchville	280978	Sussex	1954-82	NCDC
6	Culver's Lake	282130	Sussex	1931-53	NCDC
7	Layton 3	284736	Sussex	1962-70	NCDC
8	Layton 3 NW	284735	Sussex	1931-62	NCDC
9	Belvidere Bridge	280734	Warren	1893-present	NJSC
10	Belvidere	280729	Warren	1931-81	NCDC
	NEW ENGLAND PHYSIOGRAPHIC PROVINCE				
11	Mahwah	285104	Bergen	1956-88	NCDC
12	Oak Ridge Reservoir	286460	Morris	1941-present	NJSC
13	Morris Plains 1 W	285769	Morris	1941-90	NJSC
14	Long Valley	285003	Morris	1930-2004	NJSC
15	Pottersville 2 NNW	287301	Morris	1968-present	NJSC
16	Split Rock Pond	288402	Morris	1948-97	NJSC
17	Musconetcong River at Outlet of Lake Hopatcong, NJ	1455500	Morris	2002-present	USGS
18	Milton	285597	Morris	1948-72	NCDC
19	West Wharton	289608	Morris	1959-90	NCDC
20	Charlotteburg Reservoir	281582	Passaic	1893-present	NJSC

21	Greenwood Lake	283516	Passaic	1941-present	NJSC
22	Ringwood	287587	Passaic	1941-present	NJSC
23	Wanaque Raymond Dam	289187	Passaic	1945-2005	NJSC
24	Macopin L WR Intake dam	285071	Passaic	1948-60	NCDC
25	Canistear Reservoir	281327	Sussex	1948-present	NJSC
26	Great Meadows 4 N	283416	Warren	1948-51	NCDC
27	Phillipsburg	286974	Warren	1931-77	NCDC
28	Phillipsbug Easton Bridge	286979	Warren	1940-69	NCDC
	PIEDMONT PHYSIOGRAPHIC PROVINCE				
29	Midland Park	285503	Bergen	1945-present	NJSC
30	New Milford	286146	Bergen	1919-present	NJSC
31	Woodcliff Lake	289832	Bergen	1919-present	NJSC
32	Pascack Brook at Park Ridge, NJ	1377370	Bergen	2004-present	USGS
33	Pascack Bk at Woodcliff Lk Outlet at Hillsdale, NJ	1377451	Bergen	2006-present	USGS
34	Lodi	284931	Bergen	1979-93	NCDC
35	Ridgefield	287545	Bergen	1931-60	NCDC
36	Canoe Brook	281335	Essex	1931-present	NJSC
37	Essex Fells Serv Bldg	282768	Essex	1946-present	NJSC
38	Newark International Arpt	286026	Essex	1935-present	NJSC
39	Cedar Grove	281472	Essex	1948-65	NCDC
40	Essex Fells Serv Bldg.	282773	Essex	1945-49	NCDC
41	Irvington	284260	Essex	1948-64	NCDC
42	Orange	286560	Essex	1940-64	NCDC
43	Harrison	283704	Hudson	1997-present	NJSC
44	Jersey City	284339	Hudson	1905-97	NJSC
45	Flemington 5 NNW	283029	Hunterdon	1898-present	NJSC
46	Lambertville	284635	Hunterdon	1931-present	NJSC
47	Wertsville 4 NE	289363	Hunterdon	1956-present	NJSC
48	Spruce Run at Clinton, NJ	1396800	Hunterdon	2005-present	USGS

49	Clinton	281749	Hunterdon	1943-69	NCDC
50	Oldwick	286544	Hunterdon	1956-68	NCDC
51	Pleasant Run	287123	Hunterdon	1957-59	NCDC
52	Quakertown	287372	Hunterdon	1948-51	NCDC
53	Princeton Water Works	287328	Mercer	1941-86	NJSC
54	Trenton	288883	Mercer	1931-81, 2002-present	NJSC
55	Washington Crossing	--	Mercer	1981-present	NADP
56	Trenton 2	288878	Mercer	1931-59	NCDC
57	New Brunswick 3 SE	286055	Middlesex	1912-present	NJSC
58	New Brunswick EXP STN	286062	Middlesex	1931-68	NCDC
59	Boonton 1 SE	280907	Morris	1893-present	NJSC
60	Chatham	281590	Morris	1931-63	NCDC
61	Chatham 2	281592	Morris	2001-2003	NCDC
62	Little Falls	284887	Passaic	1903-present	NJSC
63	Wayne	289317	Passaic	2000-present	NJSC
64	Paterson	286775	Passaic	1931-74	NCDC
65	Rutherford	287833	Passaic	1944-51	NCDC
66	Bound Brook 2 W	280927	Somerset	1957-present	NJSC
67	Somerville 4 NW	288194	Somerset	1893-2005	NJSC
68	Pike Run at Belle Mead, NJ	1401650	Somerset	1980-present	USGS
69	West Branch Middle Brook near Martinsville, NJ	1403150	Somerset	1979-present	USGS
70	Stony Brook at Watchung, NJ	1403540	Somerset	2005-present	USGS
71	Bound Brook at Middlesex, NJ	1403900	Somerset	2003-present	USGS
72	Somerset County Admin Bldg at Somerville, NJ	403410074364001	Somerset	2002-present	USGS
73	Bernardsville 2 E	280797	Somerset	1959-79	NCDC
74	Blackwells Mills	280847	Somerset	1956-87	NCDC
75	Manville	285197	Somerset	1945-67	NCDC

76	Cranford	282023	Union	1969-present	NJSC
77	Plainfield	287079	Union	1893-present	NJSC
78	Rahway	287393	Union	1940-present	NJSC
79	Elizabeth	282644	Union	1931-70	NCDC
80	Elizabethport	282652	Union	1948-64	NCDC
81	Springfield	288423	Union	1948-51	NCDC
82	Watchung	289271	Union	1948-51	NCDC
83	Westfield	289455	Union	1939-60	NCDC
	INNER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE				
84	Moorestown	285728	Burlington	1893-present	NJSC
85	Philadelphia Mt Holly	PHIN4	Burlington	2000-present	NJSC
86	Chesterfield Township	--	Burlington	1999-present	SJRCD
87	Easthampton Township	--	Burlington	1999-present	SJRCD
88	Mansfield Township	--	Burlington	1999-present	SJRCD
89	Burlington	281211	Burlington	1931-78	NCDC
90	Lumberton	285055	Burlington	1948-51	NCDC
91	Marlton 1 W	285252	Burlington	1941-59	NCDC
92	Audubon	280346	Camden	1950-89	NJSC
93	Somerdale 4 SW	288173	Camden	1998-present	NJSC
94	Cherry Hill	--	Camden	1994-present	SJRCD
95	Brooklawn	281106	Camden	1941-49	NCDC
96	Camden	281280	Camden	1952-53	NCDC
97	Cherry Hill	281608	Camden	1973-77	NCDC
98	Pennsauken	286863	Camden	1964-68	NCDC
99	Runnemede	287817	Camden	1948-53	NCDC
100	Swedesboro	288680	Gloucester	1946-54	NCDC
101	Swedesboro 5 NW	288685	Gloucester	1946-59	NCDC
102	Hightstown Pumping STA	283956	Mercer	1948-51	NCDC
103	Hightstown 2 W	283951	Mercer	1893-present	NJSC

104	Plainsboro	287095	Middlesex	1941-48	NCDC
105	Runyon	287825	Middlesex	1931-58	NCDC
106	Freehold Marlboro	283181	Monmouth	1931-present	NJSC
107	Raritan Bay at Keansburg, NJ	1407081	Monmouth	2000-present	USGS
108	Marlboro SCS	285244	Monmouth	1948-51	NCDC
109	New Monmouth	286154	Monmouth	1961-68	NCDC
110	Sandy Hook	287865	Monmouth	1969-2006	NCDC
111	Sandy Hook Light STN	287869	Monmouth	1931-59	NCDC
112	Deepwater	282209	Salem	1948-64	NCDC
	OUTER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE				
113	Atlantic City Intl Ap	280311	Atlantic	1958-present	NJSC
114	Atlantic City State Marina	280325	Atlantic	1948-present	NJSC
115	Estell Manor	282805	Atlantic	1990-present	NJSC
116	Hammonton 2 NNE	283662	Atlantic	1931-present	NJSC
117	Mays Landing 1 W	285346	Atlantic	1944-present	NJSC
118	Albertson Brook near Hammonton, NJ	1409410	Atlantic	2004-present	USGS
119	Absecon Channel at Atlantic City, NJ	1410600	Atlantic	2000-present	USGS
120	Great Egg Harbor River at Folsom, NJ	1411000	Atlantic	1983-present	USGS
121	Hammonton	--	Atlantic	1994-present	SJRCD
122	Atlantic County Utility Company	--	Atlantic	1994-present	SJRCD
123	Edwin Forsythe Wildlife Refuge	--	Atlantic	1998-present	NADP
124	Pleasantville 1 N	287131	Atlantic	1931-58	NCDC
125	Indian Mills 2 W	284229	Burlington	1901-present	NJSC
126	Pemberton	286843	Burlington	1902-2002	NJSC
127	Southwest Branch Rancocas Creek at Medford, NJ	1465880	Burlington	2006-present	USGS
128	Greenwood Branch at New Lisbon, NJ	1466900	Burlington	1998-present	USGS
129	Bass River State Forest	280528	Burlington	1945-74	NCDC
130	Chatsworth	281598	Burlington	1940-80	NCDC

132	Erail/Berlin	--	Camden	1994-present	SJRCD
133	Berlin 1 W	280787	Camden	1941-59	NCDC
134	Sicklerville	288073	Camden	1990-91	NCDC
135	Belleplain St Forest	280690	Cape May	1922-present	NJSC
136	Cape May 2 NW	281351	Cape May	1931-present	NJSC
137	Cape May Harbor at Cape May, NJ	1411390	Cape May	2000-present	USGS
138	West Cape May	--	Cape May	1996-present	SJRCD
139	Cape May Courthouse	--	Cape May	1996-present	SJRCD
140	Dennis Township	--	Cape May	1996-present	SJRCD
141	Millville Municipal Ap	285581	Cumberland	1947-present	NJSC
142	Seabrook Farms	287936	Cumberland	1963-present	NJSC
143	Stow Creek	--	Cumberland	1998-present	SJRCD
144	Bridgeton 1 NE	281028	Cumberland	1931-57	NCDC
145	Bridgeton 2	281033	Cumberland	1948-48	NCDC
146	Bridgeton 4 NE	281038	Cumberland	1977-90	NCDC
147	Fortescue	283102	Cumberland	1948-77	NCDC
148	Leesburg State Farm	284762	Cumberland	1951-59	NCDC
149	Millville	285576	Cumberland	1941-70	NCDC
150	Shiloh	288051	Cumberland	1958-88	NCDC
151	Vineland	289135	Cumberland	1939-59	NCDC
152	Glassboro 2 NE	283291	Gloucester	1948-2004	NJSC
153	Bethel Hill Park	--	Gloucester	1993-present	SJRCD
154	Piney Hollow	--	Gloucester	1993-present	SJRCD
155	South Harrison Twp.	--	Gloucester	1993-present	SJRCD
156	Clayton	281708	Gloucester	1931-62	NCDC
157	Trenton WSO City	288883	Mercer	1948-81	NCDC
158	Long Branch Oakhurst	284987	Monmouth	1907-present	NJSC
159	Howell	--	Monmouth	1998-present	SJRCD

160	Belmar 2 SW	280721	Monmouth	1941-67	NCDC
161	Brant Beach Beach Haven	280990	Ocean	1986-present	NJSC
163	Lakehurst NAS	284596	Ocean	1945-89	NJSC
164	Toms River	288816	Ocean	1893-present	NJSC
165	Tuckerton	288899	Ocean	1898-present	NJSC
166	Toms River	--	Ocean	1998-present	SJRCD
167	Lakewood 2 ENE	284627	Ocean	1931-56	NCDC
168	Laurelton 1 E	284700	Ocean	1957-61	NCDC
169	Woodstown	289910	Salem	1901-2003	NJSC
170	Canton	281343	Salem	1945-73	NCDC

Table 1-2. Selected information for surface-water data-collection stations active in New Jersey in water year 2006.

[ID, identification number; present, 2007; --, not available; station locations shown in Figure 11]

Map ID	Station name	Station ID	County	Period of record	Station type	Status
	VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCE					
1	Papakating Creek at Pellettown, NJ	1367800	Sussex	2003-present	Streamgage	Active
2	Wallkill River near Unionville, NJ	1368000	Sussex	1938-81	Streamgage	Inactive
3	Delaware River at Montague, NJ	1438500	Sussex	1940-54, 1955-present	Streamgage	Active
4	Flat Brook near Flatbrookville, NJ	1440000	Sussex	1924-present	Streamgage	Active
5	East Brook Paulins Kill near Lafayette, NJ	1443280	Sussex	1992-present	Streamgage	Active
6	Pequest River at Huntsville, NJ	1445000	Sussex	1940-62, 2003-present	Streamgage	Active
7	Paulins Kill at Blairstown, NJ	1443500	Warren	1922-present	Streamgage	Active
8	Yards Creek near Blairstown, NJ	1443900	Warren	1967-present	Streamgage	Active
9	Beaver Brook near Belvidere, NJ	1446000	Warren	1923-61, 2003-present	Streamgage	Active
10	Delaware River at Belvidere, NJ	1446500	Warren	1923-54, 1955-present	Streamgage	Active
11	Brass Castle Creek near Washington, NJ	1455160	Warren	1970-83	Streamgage	Inactive
	NEW ENGLAND PHYSIOGRAPHIC PROVINCE					
12	South Branch Raritan River near High Bridge, NJ	1396500	Hunterdon	1919-present	Streamgage	Active
13	Spruce Run at Glen Gardner, NJ	1396580	Hunterdon	1978-1988, 1992-present	Streamgage	Active
14	Upper Cold Brook near Pottersville, NJ	1399510	Hunterdon	1973-96	Streamgage	Inactive
15	Russia Brook Tributary at Milton, NJ	1379630	Morris	1969-71	Streamgage	Inactive
16	Rockaway River at Berkshire Valley, NJ	1379700	Morris	1985-96	Streamgage	Inactive
17	Green Pond Brook at Picatinny Arsenal, NJ	1379773	Morris	1983-present	Streamgage	Active
18	Green Pond Brook below Picatinny Lake at Picatinny Arsenal, NJ	1379780	Morris	1985-present	Streamgage	Active
19	Green Pond Brook at Wharton, NJ	1379790	Morris	1984-present	Streamgage	Active
20	Beaver Brook at outlet of Splitrock Reservoir, NJ	1380000	Morris	1926-46, 1976-89	Streamgage	Inactive
21	Rockaway River above reservoir at Boonton, NJ	1380500	Morris	1938-present	Streamgage	Active

22	Whippany River near Morristown, NJ	1381400	Morris	1995-present	Streamgage	Active
23	Pequannock River at Macopin intake dam, NJ	1382500	Morris	1923-present	Streamgage	Active
24	Pequannock River at Riverdale, NJ	1382800	Morris	1994-97	Streamgage	Inactive
25	South Branch Raritan River at Four Bridges, NJ	1396190	Morris	1999-present	Streamgage	Active
26	Lamington (Black) River at Succasunna, NJ	1399190	Morris	1976-87	Streamgage	Inactive
27	Lamington (Black) River near Ironia, NJ	1399200	Morris	1975-87	Streamgage	Inactive
28	Lamington (Black) River near Pottersville, NJ	1399500	Morris	1922-present	Streamgage	Active
29	Beaver Brook near Weldon, NJ	1455355	Morris	1969-71	Streamgage	Inactive
30	Musconetcong River at outlet of Lake Hopatcong, NJ	1455500	Morris	1928-75	Streamgage	Active
31	Auxilary outlet of Upper Greenwood Lake at Moe, NJ	1368720	Passaic	1968-80	Streamgage	Inactive
32	Greenwood Lake at Awosting, NJ	1383000	Passaic	1898-1903, 1907-present	Streamgage	Active
33	Wanaque River at Awosting, NJ	1383500	Passaic	1919-present	Streamgage	Active
34	Wanaque River at Monks, NJ	1384000	Passaic	1935-85	Streamgage	Inactive
35	Ringwood Creek near Wanaque, NJ	1384500	Passaic	1935-79, 1986-present	Streamgage	Active
36	Cupsaw Brook near Wanaque, NJ	1385000	Passaic	1936-58	Streamgage	Inactive
37	Erskine Brook near Wanaque, NJ	1385500	Passaic	1934-38	Streamgage	Inactive
38	West Brook near Wanaque, NJ	1386000	Passaic	1935-78	Streamgage	Active
39	Blue Mine Brook near Wanaque, NJ	1386500	Passaic	1935-58	Streamgage	Inactive
40	Wanaque Reservoir at Wanaque, NJ	1386990	Passaic	1928-50, 1953-present	Streamgage	Active
41	Wanaque River at Wanaque, NJ	1387000	Passaic	1912-2005	Streamgage	Active
42	North Branch Raritan River near Far Hills, NJ	1398500	Somerset	1922-75, 1977-present	Streamgage	Active
43	Pequest River at Townsbury, NJ	1445430	Warren	1977-80	Streamgage	Inactive
44	Pequest River at Pequest, NJ	1445500	Warren	1922-present	Streamgage	Active
45	Pohatcong Creek at New Village, NJ	1455200	Warren	1960-69	Streamgage	Inactive
46	Musconetcong River near Hackettstown, NJ	1456000	Warren	1922-73	Streamgage	Inactive
47	Musconetcong River near Bloomsbury, NJ	1457000	Warren	1903-04, 1910-present	Streamgage	Active
48	Delaware River at Riegelsville, NJ	1457500	Warren	1906-53, 1954-present	Streamgage	Inactive

PIEDMONT PHYSIOGRAPHIC PROVINCE						
49	Hackensack River at Rivervale, NJ	1377000	Bergen	1942-56, 1957-present	Streamgage	Active
50	Pascack Brook at Westwood, NJ	1377500	Bergen	1935-present	Streamgage	Active
51	Hackensack River at New Milford, NJ	1378500	Bergen	1922-present	Streamgage	Active
52	Hackensack River below dam at New Milford, NJ	1378501	Bergen	1997-present	Tide crest-stage	Active
53	Hackensack River at Hackensack, NJ	1378570	Bergen	1998-present	Tide gage	Active
54	Hackensack River at NJ Route 3 near Lynhurst, NJ	1378626	Bergen	1997-present	Tide crest-stage	Active
55	Ramapo River near Mahwah, NJ	1387500	Bergen	1903-06, 1923-present	Streamgage	Active
56	Ramapo River downstream of Pond Brook at Oakland, NJ	1387890	Bergen	1999-present	Streamgage	Inactive
57	Passaic River at Garfield, NJ	1390000	Bergen	1997-present	Tide crest-stage	Active
58	Saddle River at Upper Saddle River, NJ	1390450	Bergen	2003-present	Streamgage	Active
59	Saddle River at Ridgewood, NJ	1390500	Bergen	1955-75, 1978-present	Streamgage	Active
60	Hohokus Brook at Ho-Ho-Kus, NJ	1391000	Bergen	1955-74, 1977-present	Streamgage	Inactive
61	Saddle River at Lodi, NJ	1391500	Bergen	1923-65, 1966-present	Streamgage	Active
62	Deepavaal Brook near Fairfield, NJ	1389130	Essex	1993-97	Streamgage	Inactive
63	Second River at Belleville, NJ	1392500	Essex	1938-64	Streamgage	Inactive
64	Elizabeth River at Irvington, NJ	1393000	Essex	1931-38	Streamgage	Inactive
65	East Fork East Branch Rahway River at West Orange, NJ	1393800	Essex	1972-74	Streamgage	Inactive
66	West Branch Rahway River at Millburn, NJ	1394000	Essex	1940-50	Streamgage	Inactive
67	Passaic River at PVSC at Newark, NJ	1392650	Essex	--	Tide gage	Active
68	Mulhockaway Creek at Van Syckel, NJ	1396660	Hunterdon	1977-present	Streamgage	Active
69	Spruce Run at Clinton, NJ	1396800	Hunterdon	1961-63, 1964-present	Streamgage	Active
70	South Branch Raritan River at Stanton, NJ	1397000	Hunterdon	1920-63, 1964-present	Streamgage	Active
71	Walnut Brook near Flemington, NJ	1397500	Hunterdon	1937-61	Streamgage	Inactive
72	Neshanic River at Reaville, NJ	1398000	Hunterdon	1931-present	Streamgage	Active
73	Back Brook Tributary near Ringoes, NJ	1398045	Hunterdon	1977-88	Streamgage	Inactive
74	South Branch Rockaway Creek at Whitehouse Station,	1399670	Hunterdon	1977-present	Streamgage	Active

	NJ					
75	South Branch Rockaway Creek at Whitehouse, NJ	1399690	Hunterdon	1977-86	Streamgage	Inactive
76	Rockaway Creek at Whitehouse, NJ	1399700	Hunterdon	1977-84	Streamgage	Inactive
77	Delaware River at Lambertville, NJ	1462000	Hunterdon	1898-1906	Streamgage	Inactive
78	Baldwins Creek at Baldwin Lake near Pennington, NJ	1400932	Mercer	1963-70	Streamgage	Inactive
79	Honey Branch near Pennington, NJ	1400953	Mercer	1967-75	Streamgage	Inactive
80	Stony Brook at Princeton, NJ	1401000	Mercer	1954-present	Streamgage	Active
81	Delaware and Raritan Canal at Port Mercer, NJ	1460440	Mercer	1990-present	Streamgage	Active
82	Shipetaukin Creek Tributary at Lawrenceville, NJ	1463657	Mercer	1976-77	Streamgage	Inactive
83	Lower Shabakunk Creek at Bakersville, NJ	1463690	Mercer	1976-77	Streamgage	Inactive
84	Rahway River at US Route 1 at Rahway, NJ	1396035	Middlesex	1997-present	Tide crest-stage	Active
85	Millstone River at Carnegie Lake at Princeton, NJ	1401301	Middlesex	1972-74, 1987-89	Streamgage	Inactive
86	Millstone River near Kingston, NJ	1401500	Middlesex	1934-49	Streamgage	Inactive
87	Raritan River at NJ Route 18 at New Brunswick, NJ	1404171	Middlesex	1997-present	Tide crest-stage	Active
88	Lawrence Brook at Patrick's Corner, NJ	1404500	Middlesex	1922-26	Streamgage	Inactive
89	Lawrence Brook at Farrington Dam, NJ	1405000	Middlesex	1927-90	Streamgage	Inactive
90	Lawrence Brook at Westons Mills, NJ	1405030	Middlesex	1989-94, 1995-present	Streamgage	Active
91	Deep Run at Old Bridge, NJ	1406050	Middlesex	2001-present	Streamgage	Active
92	Delaware and Raritan Canal at Carnegie Lake, NJ	1460490	Middlesex	1951-99	Streamgage	Inactive
93	Delaware and Raritan Canal at Kingston, NJ	1460500	Middlesex	1947-present	Streamgage	Inactive
94	Passaic River near Chatham, NJ	1379500	Morris	1903-12, 1938-present	Streamgage	Active
95	Canoe Brook near Summit, NJ	1379530	Morris	1996-present	Streamgage	Active
96	Passaic River near Hanover Neck, NJ	1379580	Morris	1993-97	Streamgage	Inactive
97	Rockaway River below reservoir at Boonton, NJ	1381000	Morris	1950-present	Streamgage	Active
98	Whippany River at Morristown, NJ	1381500	Morris	1922-present	Streamgage	Active
99	Whippany River near Pine Brook, NJ	1381800	Morris	1997-present	Streamgage	Active
100	Passaic River at Pine Brook, NJ	1381900	Morris	1980-present	Streamgage	Active
101	Passaic River at Towaco, NJ	1381950	Morris	1993-97	Streamgage	Inactive
102	Ramapo River at Pompton Lakes, NJ	1388000	Passaic	1922-present	Streamgage	Active

103	Pompton River at Pompton Plains, NJ	1388500	Passaic	1903-04, 1941-present	Streamgage	Active
104	Pompton River at Mountain View, NJ	1388910	Passaic	1993-97	Streamgage	Inactive
105	Passaic River at Little Falls, NJ	1389500	Passaic	1897-1927, 1928-present	Streamgage	Active
106	Passaic River at Paterson, NJ	1389800	Passaic	1897-1955	Streamgage	Inactive
107	Weasel Brook at Clifton, NJ	1392000	Passaic	1938-50, 1951-62	Streamgage	Inactive
108	Third River at Passaic, NJ	1392210	Passaic	1977-97	Streamgage	Inactive
109	Passaic River near Bernardsville, NJ	1378690	Somerset	1968-77	Streamgage	Inactive
110	Passaic River near Millington, NJ	1379000	Somerset	1903-06, 1922-present	Streamgage	Active
111	Holland Brook at Readington, NJ	1398107	Somerset	1978-95	Streamgage	Inactive
112	Axle Brook near Pottersville, NJ	1399525	Somerset	1977-88	Streamgage	Inactive
113	North Branch Raritan River at North Branch, NJ	1399830	Somerset	1977-81	Streamgage	Inactive
114	North Branch Raritan River near Raritan, NJ	1400000	Somerset	1924-present	Streamgage	Active
115	North Branch Raritan River at South Branch, NJ	1400010	Somerset	2003-present	Streamgage	Active
116	Peters Brook near Raritan, NJ	1400300	Somerset	1978-1995	Streamgage	Inactive
117	Macs Brook at Somerville, NJ	1400350	Somerset	1982-1995	Streamgage	Inactive
118	Raritan River at Manville, NJ	1400500	Somerset	1904-1906, 1922-1963, 1964-present	Streamgage	Active
119	Pike Run at Belle Mead, NJ	1401650	Somerset	1981-present	Streamgage	Active
120	Millstone River at Blackwells Mills, NJ	1402000	Somerset	1922-present	Streamgage	Active
121	Royce Brook Tributary at Frankfort, NJ	1402590	Somerset	1969-1974	Streamgage	Inactive
122	Royce Brook Tributary near Belle Mead, NJ	1402600	Somerset	1967-74, 1981-96	Streamgage	Inactive
123	Raritan River at Bound Brook, NJ	1403000	Somerset	1903-09, 1945-66	Streamgage	Inactive
124	Raritan River below Calco Dam at Bound Brook, NJ	1403060	Somerset	1904-08, 1945-63, 1964-present	Streamgage	Active
125	West Branch Middle Brook near Martinsville, NJ	1403150	Somerset	1980-present	Streamgage	Active
126	West Branch Middle Brook near Somerville, NJ	1403160	Somerset	1983-86	Streamgage	Inactive
127	Green Brook at Seeley Mills, NJ	1403400	Somerset	1980-present	Streamgage	Active
128	East Branch Stony Brook at Best Lake at Watchung, NJ	1403535	Somerset	1981-present	Streamgage	Inactive

129	Stony Brook at Watchung, NJ	1403540	Somerset	1975-present	Streamgage	Active
130	Bound Brook at Middlesex, NJ	1403900	Somerset	1972-77, 1997-98, 2003	Streamgage	Active
131	Bound Brook at Bound Brook, NJ	1404000	Somerset	1923-30	Streamgage	Inactive
132	Elizabeth River at Ursino Lake at Elizabeth, NJ	1393450	Union	1922-51, 1952-present	Streamgage	Active
133	Elizabeth River at Elizabeth, NJ	1393500	Union	1922-73	Streamgage	Inactive
134	Elizabeth River at Linden, NJ	1393510	Union	1997-present	Tide crest-stage	Active
135	Rahway River near Springfield, NJ	1394500	Union	1939-present	Streamgage	Active
136	Rahway River at Rahway, NJ	1395000	Union	1922-present	Streamgage	Active
137	Robinsons Branch at Goodmans, NJ	1395500	Union	1921-24	Streamgage	Inactive
138	Robinsons Branch at Rahway, NJ	1396000	Union	1940-96	Streamgage	Inactive
139	Green Brook at Plainfield, NJ	1403500	Union	1939-85	Streamgage	Inactive
140	Hackensack River at West Nyack, NY	1376800	NY State	1959-present	Streamgage	Active
	INNER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE					
141	Thorton Creek at Bordentown, NJ	1464525	Burlington	1976-77	Streamgage	Inactive
142	Delaware River at Burlington, NJ	1464598	Burlington	1964-present	Tide gage	Active
143	Mill Creek near Willingboro, NJ	1467019	Burlington	1975-78	Streamgage	Inactive
144	Mill Creek at Levitt Parkway at Willingboro, NJ	1467021	Burlington	1975-77	Streamgage	Inactive
145	South Branch Pennsauken Creek at Cherry Hill, NJ	1467081	Camden	1967-present	Streamgage	Active
146	Cooper River at Haddonfield, NJ	1467150	Camden	1964-87, 1988-present	Streamgage	Active
147	Still Run near Mickleton, NJ	1476600	Gloucester	1957-66	Streamgage	Inactive
148	Raccoon Creek near Swedesboro, NJ	1477120	Gloucester	1967-present	Streamgage	Active
149	Delaware River near Gibbstown, NJ	1476550	Gloucester	1972-77, 1979-85, 1997-present	Streamgage	Active
150	Delaware River at marine terminal Trenton, NJ	1464040	Mercer	1921-46, 1951-55, 1957-92, 1997-present	Tide crest-stage	Active
151	Crosswicks Creek at Extonville, NJ	1464500	Mercer	1940-51, 1953-present	Streamgage	Active
152	Matchaponix Brook at Spotswood, NJ	1405300	Middlesex	1957-67	Streamgage	Inactive
153	Manalapan Brook at Spotswood, NJ	1405400	Middlesex	1958-present	Streamgage	Active
154	South River at Old Bridge, NJ	1405500	Middlesex	1939-88	Streamgage	Inactive
155	Deep Run near Browntown, NJ	1406000	Middlesex	1932-40	Streamgage	Inactive

156	Tennent Brook near Browntown, NJ	1406500	Middlesex	1932-41	Streamgage	Inactive
157	Raritan River at Perth Amboy, NJ	1406700	Middlesex	1980-present	Tide crest-stage	Active
158	Rraitan River at South Amboy, NJ	1406710	Middlesex	1998-present	Tide gage	Active
159	Matawan Creek at Matawan, NJ	1407000	Monmouth	1933-55	Streamgage	Inactive
160	Luppatatong Creek at Keyport, NJ	1407030	Monmouth	1980-present	Tide crest-stage	Active
161	Waackaack Creek at Keansburg, NJ	1407080	Monmouth	1998-present	Tide gage	Active
162	Big Brook near Marlboro, NJ	1407290	Monmouth	2003-present	Streamgage	Active
163	Swimming River near Red Bank, NJ	1407500	Monmouth	1923-present	Streamgage	Active
164	Navesink River at Red Bank, NJ	1407535	Monmouth	1997-present	Tide crest-stage	Active
165	Shrewsbury River at Sea Bright, NJ	1407600	Monmouth	1998-present	Tide gage	Active
166	Oldman's Creek near Woodstown, NJ	1477500	Salem	1932-40	Streamgage	Inactive
217	New Sharon Run at Carsons Mills, NJ	1463587	Mercer	1976-77	Streamgage	Inactive
	OUTER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE					
167	Mullica River near Batsto, NJ	1409400	Atlantic	1958-present	Streamgage	Active
168	Mullica River near Port Republic, NJ	1410100	Atlantic	1962, 1965-present	Tide crest-stage	Active
169	Absecon Creek at Absecon, NJ	1410500	Atlantic	1947-84	Streamgage	Inactive
170	Absecon Creek at Absecon, NJ	1410500	Atlantic	1985-present	Tide crest-stage	Active
171	Absecon Creek at US Route 30 at Absecon, NJ	1410510	Atlantic	1998-present	Tide gage	Active
172	Inside Thorofare at US Route 40 at Atlantic City, NJ	1410560	Atlantic	1998-present	Tide gage	Active
173	Beach Thorofare at Atlantic City, NJ	1410570	Atlantic	1969-present	Tide crest-stage	Active
174	Great Egg Harbor River at Folsom, NJ	1411000	Atlantic	1926-present	Streamgage	Active
175	Great Egg Harbor River at US Route 40 at Mays Landing, NJ	1411175	Atlantic	1997-present	Tide crest-stage	Active
176	Tuckahoe River at head of river, NJ	1411300	Atlantic	1971-present	Streamgage	Active
177	Lakes Bay at Pleasantville, NJ	1411325	Atlantic	1997-present	Tide crest-stage	Active
178	Beach Thorofare at Margate, NJ	1411330	Atlantic	1998-present	Tide gage	Active
179	Batsto River at Batsto, NJ	1409500	Burlington	1928-present	Streamgage	Active
180	Batsto River at Pleasant Mills, NJ	1409510	Burlington	1958-present	Tide crest-stage	Active

181	West Branch Wading River near Jenkins, NJ	1409810	Burlington	1975-96	Streamgage	Inactive
182	Oswego River at Harrisville, NJ	1410000	Burlington	1931-present	Streamgage	Active
183	East Branch Bass River near New Gretna, NJ	1410150	Burlington	1979-present	Streamgage	Active
184	South Branch Rancocas Creek at Vincentown, NJ	1465850	Burlington	1962-75, 1999-present	Streamgage	Active
185	Middle Branch Mount Misery Brook in Lebanon State Forest, NJ	1466000	Burlington	1953-65, 1977	Streamgage	Inactive
186	McDonalds Branch in Lebanon State Forest, NJ	1466500	Burlington	1954-present	Streamgage	Active
187	Greenwood Brook at New Lisbon, NJ	1466900	Burlington	1998-present	Streamgage	Active
188	North Branch Rancocas Creek at Pemberton, NJ	1467000	Burlington	1922-present	Streamgage	Active
189	Great Egg Harbor River near Sicklerville, NJ	1410784	Camden	1996-98	Streamgage	Inactive
190	Great Egg Harbor River Tributary at Sicklerville, NJ	1410787	Camden	1972-79	Streamgage	Inactive
191	Fourmile Branch at New Brooklyn, NJ	1410810	Camden	1973-79	Streamgage	Inactive
192	Great Egg Harbor River near Blue Anchor, NJ	1410820	Camden	1972-79	Streamgage	Inactive
193	Grassy Sound Channel at Nummy Island near North Wildwood, NJ	1411370	Cape May	1993-96, 1997-present	Tide crest-stage	Active
194	Great Egg Harbor Bay at Beesley's Point, NJ	1411315	Cape May	1963-78, 1979-81, 1997-present	Tide crest-stage	Active
195	Peck Bay at Ocean City, NJ	1411318	Cape May	2000-present	Tide gage	Active
196	Great Egg Harbor Bay at Ocean City, NJ	1411320	Cape May	1965-present	Tide crest-stage	Active
197	Strathmere Bay at Strathmere, NJ	1411335	Cape May	1997-present	Tide crest-stage	Active
198	Ludlum Thorofare at Sea Isle City, NJ	1411350	Cape May	2000-present	Tide gage	Active
199	Ingram Thorofare at Avalon, NJ	1411355	Cape May	2000-present	Tide gage	Active
200	Great Channel at Stone Harbor, NJ	1411360	Cape May	2000-present	Tide gage	Active
201	Grassy Sound Channel at Wildwood, NJ	1411382	Cape May	1998-present	Tide gage	Active
202	Sluice Creek near South Dennis, NJ	1411435	Cape May	1998-present	Tide gage	Active
203	Blackwater Branch at Norma, NJ	1411495	Cumberland	1992-94	Streamgage	Inactive
204	Maurice River near Millville, NJ	1411800	Cumberland	1992-94	Streamgage	Inactive
205	Maurice River at Union Lake Dam at Millville, NJ	1411878	Cumberland	1993-94	Streamgage	Inactive
206	Maurice River at Millville, NJ	1411900	Cumberland	1997-present	Tide crest-stage	Active

207	Menantico Creek near Millville, NJ	1412000	Cumberland	1932-57, 1978-84	Streamgage	Inactive
208	Maurice River at Bivalve, NJ	1412150	Cumberland	1998-present	Tide gage	Active
209	West Branch Cohansey River at Seeley, NJ	1412500	Cumberland	1951-67	Streamgage	Inactive
210	Cohansey River at Seeley, NJ	1412800	Cumberland	1978-88, 2003-present	Streamgage	Active
211	Loper Run near Bridgeton, NJ	1413000	Cumberland	1937-59	Streamgage	Inactive
212	Cohansey River at Bridgeton, NJ	1413015	Cumberland	1997-present	Tide crest-stage	Active
213	Cohansey River at Greenwich, NJ	1413038	Cumberland	1998-present	Tide gage	Active
214	Little Ease Run near Clayton, NJ	1411456	Gloucester	1988-present	Streamgage	Active
215	Mantua Creek at Pitman, NJ	1475000	Gloucester	1941-76, 2003-present	Streamgage	Active
216	Delaware River near Gibbstown, NJ	1476550	Gloucester	1972-77, 1979-85, 1997-present	Streamgage	Active
217	Delaware River at Trenton, NJ	1463500	Mercer	1913-54, 1955-present	Streamgage	Active
218	Assunpink Creek near Clarksville, NJ	1463620	Mercer	1973-81, 1996-present	Streamgage	Active
219	Assunpink Creek at Trenton, NJ	1464000	Mercer	1924-54, 1955-present	Streamgage	Active
220	Millstone River at Plainsboro, NJ	1400730	Middlesex	1964-75, 1987-89	Streamgage	Inactive
221	Branchport Creek at Oceanport, NJ	1407590	Monmouth	1997-present	Tide crest-stage	Active
222	Shark River near Neptune City, NJ	1407705	Monmouth	1967-present	Streamgage	Active
223	Jumping Brook near Neptune City, NJ	1407760	Monmouth	1967-present	Streamgage	Active
224	Shark River at Belmar, NJ	1407770	Monmouth	1998-2002, 2004-present	Tide gage	Active
225	Manasquan River at Squankum, NJ	1408000	Monmouth	1932-present	Streamgage	Active
226	Manasquan River near Allenwood, NJ	1408029	Monmouth	1990-present	Streamgage	Active
227	North Branch Metedeconk River near Lakewood, NJ	1408120	Ocean	1973-present	Streamgage	Active
228	South Metedeconk River at Lakewood, NJ	1408140	Ocean	1973-76	Streamgage	Inactive
229	South Branch Metedeconk River near Lakewood, NJ	1408150	Ocean	1992-99	Streamgage	Inactive
230	Metedeconk River at Laurelton, NJ	1408155	Ocean	1997-present	Tide crest-stage	Active
231	Barnegat Bay at Mantoloking, NJ	1408168	Ocean	1998-present	Tide gage	Active
232	Toms River near Toms River, NJ	1408500	Ocean	1929-66, 1967-present	Streamgage	Active
233	Toms River at Toms River, NJ	1408700	Ocean	1997-present	Tide crest-stage	Active
234	Barnegat Bay at Seaside Heights, NJ	1408750	Ocean	1998-present	Tide gage	Active
235	Cedar Creek at Lanoka Harbor, NJ	1409000	Ocean	1933-58, 1971, 2003-present	Streamgage	Active

236	Oyster Creek near Brookville, NJ	1409095	Ocean	1965-84	Streamgage	Inactive
237	Barnegat Bay at Waretown, NJ	1409110	Ocean	1993-present	Tide gage	Active
238	Barnegat Bay at Loveladies, NJ	1409135	Ocean	1993-2002, 2004-present	Tide crest-stage	Active
239	Manahawkin Bay near Manahawkin, NJ	1409145	Ocean	1965-present	Tide crest-stage	Active
240	East Thorofare at Ship Bottom, NJ	1409146	Ocean	1998-present	Tide gage	Active
241	Westecunk Creek at Stafford Forge, NJ	1409280	Ocean	1974-88, 2003-present	Streamgage	Active
242	Little Egg Harbor at Beach Haven, NJ	1409285	Ocean	1979-present	Tide crest-stage	Active
243	Little Egg Inlet near Tuckerton, NJ	1409335	Ocean	1971-75	Tide gage	Active
244	Maurice River at Brotmanville, NJ	1411485	Salem	1992-94	Streamgage	Inactive
245	Maurice River at Norma, NJ	1411500	Salem	1933-present	Streamgage	Active
246	Salem River at Woodstown, NJ	1482500	Salem	1940-85, 1989-present	Streamgage	Active
247	Alloway Creek at Alloway, NJ	1483000	Salem	1953-72, 2003	Streamgage	Inactive
248	Alloway Creek at Hancocks Bridge, NJ	1483050	Salem	1980-85, 1993, 1997-present	Tide crest-stage	Active
249	Salem River at Salem, NJ	1482650	Salem	1997-present	Tide crest-stage	Active

Table 1-3. Selected information for monitoring wells active in New Jersey in water year 2006.

[ID, identification number; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; well locations shown in Figure 18]

Map ID	Station ID	County	Aquifer type	Data-collection frequency	Available in real-time	Record start date	Land-surface elevation (ft above NGVD 29)	Well depth (ft below land surface)
VALLEY AND RIDGE PHYSIOGRAPHIC PROVINCE								
1	410928074522801	Sussex	Valley-fill	Daily	No	1991	425.3	55
2	410914074540401	Sussex	Bedrock	Daily	Yes	1988	480	95
3	410804074424401	Sussex	Valley-fill	Daily	No	1991	528.5	80
4	410449074483301	Sussex	Bedrock	Daily	Yes	1991	514.1	148
5	410431074395801	Sussex	Valley-fill	Daily	No	1991	621.7	143
6	410005074473801	Sussex	Bedrock	Daily	No	1991	648.5	500
7	405808074583001	Warren	Bedrock	Daily	No	1999	460	294
NEW ENGLAND PHYSIOGRAPHIC PROVINCE								
8	410207074270001	Morris	Valley-fill	Daily	Yes	1981	758.56	120
9	405531074361901	Morris	Valley-fill	Daily	No	1981	725.64	98
10	405414074354201	Morris	Valley-fill	Daily	No	1991	669.1	100
11	405123074375701	Morris	Valley-fill	Daily	No	1989	704.2	154
12	404934074400501	Morris	Water-table	Daily	Yes	1991	890	200
13	404921074335601	Morris	Bedrock	Semi-annually	No	1964	800	218
14	405613074430901	Sussex	Bedrock	Daily	No	1994	732	100
15	403719075091801	Warren	Valley-fill	Daily	Yes	2003	190	12
PIEDMONT PHYSIOGRAPHIC PROVINCE								
16	410155074060201	Bergen	Bedrock	Daily	No	1991	148.9	175
17	404452074211601	Essex	Valley-fill	Semi-annually	No	1950	170	130
18	404455074203202	Essex	Valley-fill	Daily	No	1991	184.7	84
19	404454074202101	Essex	Valley-fill	Semi-annually	No	1926	179.37	64

20	404347074193301	Essex	Valley-fill	Semi-annually	No	1991	276.9	200
21	403517074452501	Hunterdon	Bedrock	Daily	Yes	1990	224.99	101
22	403455074514801	Hunterdon	Bedrock	Daily	Yes	1991	170.4	175
23	402644074563601	Hunterdon	Water-table	Daily	No	1965	342.08	21
24	402151074525301	Hunterdon	Bedrock	Daily	Yes	1989	405	299
25	402131074461201	Mercer	Bedrock	Semi-annually	No	1967	179.53	150
26	402138074435801	Mercer	Bedrock	Daily	No	1987	231	99
27	401834074515501	Mercer	Bedrock	Daily	No	1991	183.3	225
28	401753074483501	Mercer	Bedrock	Daily	No	1986	212	300
29	401804074432601	Mercer	Bedrock	Daily	Yes	1990	123.2	200
30	401552074501801	Mercer	Bedrock	Daily	No	1964	122.99	300
31	405027074232301	Morris	Valley-fill	Daily	No	1966	192.07	89
32	404937074220001	Morris	Valley-fill	Semi-annually	No	1967	181	104
33	404826074234701	Morris	Valley-fill	Semi-annually	No	1966	188.25	123
34	404816074235901	Morris	Valley-fill	Semi-annually	No	1966	174.91	110
35	404748074241901	Morris	Valley-fill	Semi-annually	No	1966	178.26	108
36	404639074230001	Morris	Valley-fill	Daily	No	1967	198	110
37	404510074240201	Morris	Valley-fill	Semi-annually	No	1955	194.9	100
38	404432074225301	Morris	Valley-fill	Semi-annually	No	1967	218.8	150
39	403200074420601	Somerset	Bedrock	Daily	No	2003	60	36
40	402512074414301	Somerset	Bedrock	Daily	No	2003	110	40
41	404111074121701	Union	Bedrock	Semi-annually	No	1956	28.23	660
42	404106074171901	Union	Bedrock	Daily	Yes	1943	69	290
43	404044074162101	Union	Bedrock	Semi-annually	No	1952	96.2	251
44	404027074164401	Union	Bedrock	Semi-annually	No	1952	85.22	251
INNER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE								
45	395928074502701	Burlington	Water-table	Daily	Yes	2003	17	14
46	402553074271701	Middlesex	Water-table	Daily	Yes	1936	73	21

47	402608074195701	Middlesex	Water-table	Semi-annually	No	1968	35.27	82
48	402558074201301	Middlesex	Water-table	Semi-annually	No	1968	22.19	37
49	402143074185201	Middlesex	Water-table	Daily	Yes	1923	76.75	11
50	401932074352901	Middlesex	Water-table	Semi-annually	No	1970	76	75
51	401229074290001	Monmouth	Water-table	Daily	No	2005	152	18.5
52	394317075261901	Salem	Water-table	Semi-annually	No	1959	25.4	18
OUTER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE								
53	393333074442401	Atlantic	Water-table	Daily	Yes	1962	93.19	275
54	393232074263902	Atlantic	Water-table	Bimonthly	No	1985	38.1	182
55	393232074263903	Atlantic	Water-table	Daily	No	1985	38.1	93
56	400148074352101	Burlington	Water-table	Daily	No	1996	113.49	20
57	395150074284201	Burlington	Water-table	Daily	Yes	1955	152.02	33
58	395122074301702	Burlington	Water-table	Daily	No	1965	140.82	170
59	394513074280601	Burlington	Water-table	Daily	No	1937	104.3	41
60	394452074281901	Burlington	Water-table	Daily	No	1936	78.78	12
61	394106074362501	Burlington	Water-table	Daily	No	1955	63.24	25
62	394422074430902	Burlington	Water-table	Bimonthly	No	1963	47.52	65
63	394422074430903	Burlington	Water-table	Daily	No	1963	47.13	17
64	394440074593101	Camden	Water-table	Daily	Yes	1971	173.26	76
65	391145074520401	Cape May	Water-table	Daily	No	2001	10	11
66	390211074505502	Cape May	Water-table	Daily	No	1957	14.9	26
67	390156074533401	Cape May	Water-table	Daily	Yes	1992	20	43
68	385616074580001	Cape May	Water-table	Semi-annually	No	1967	9.12	20
69	392920074570001	Cumberland	Water-table	Daily	No	1972	88	81
70	393238075134701	Cumberland	Water-table	Daily	No	2005	139.64	44
71	393104075150801	Cumberland	Water-table	Daily	No	2005	103.62	22.2
72	393101075141702	Cumberland	Water-table	Daily	No	2005	112.87	35
73	393033075145302	Cumberland	Water-table	Daily	No	2005	96.87	35

74	393013075152802	Cumberland	Water-table	Daily	No	2005	73.66	25
75	392731075092401	Cumberland	Water-table	Daily	Yes	1972	81.77	47
76	392732075092401	Cumberland	Water-table	Bimonthly	No	1972	82.14	138
77	392508075184601	Cumberland	Water-table	Semi-annually	No	1973	37.35	40
78	391830075120801	Cumberland	Water-table	Semi-annually	No	1972	10.1	171
79	394354075025901	Gloucester	Water-table	Daily	No	1989	150	54
80	394256075101001	Gloucester	Water-table	Daily	No	1997	140	33
81	394221075072201	Gloucester	Water-table	Daily	No	1991	153.9	36
82	393749074550901	Gloucester	Water-table	Daily	No	1997	97	15
83	393246075012701	Gloucester	Water-table	Daily	No	1987	120	154
84	400416074270104	Ocean	Water-table	Bimonthly	No	1964	135.31	71
85	400232074213201	Ocean	Water-table	Daily	Yes	1992	110	38
86	400120074265401	Ocean	Water-table	Daily	No	1992	180	75
87	395034074112101	Ocean	Water-table	Daily	No	2003	19	20
88	394742074142001	Ocean	Water-table	Bimonthly	No	1962	44.25	21
89	394742074142002	Ocean	Water-table	Daily	No	1962	43.82	316
90	394829074053501	Ocean	Water-table	Bimonthly	No	1962	8.5	397
91	394829074053504	Ocean	Water-table	Semi-annually	No	1962	8.19	12

Table 1-4. Selected information for evapotranspiration data-collection sites active in New Jersey in 2006.

[ID, identification number; ft, feet; NGVD 29, National Geodetic Vertical Datum of 1929; --, not available; NCDC, National Climatic Data Center; SJRCD, South Jersey Resource and Conservation Development; present, 2007; station locations shown in Figure 20]

Map ID	Station name	Land-surface elevation (ft above NGVD 29)	Period of record	Source agency
PIEDMONT PHYSIOGRAPHIC PROVINCE				
1	New Brunswick 3E	--	1968-present	NCDC
INNER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE				
8	Cherry Hill	28	1994-present	SJRCD
15	Chesterfiled Township	112	1999-present	SJRCD
16	Easthampton Township	52	1999-present	SJRCD
17	Mansfield Township	70	1999-present	SJRCD
OUTER COASTAL PLAIN PHYSIOGRAPHIC PROVINCE				
2	Eethel Hill Park	100	1993-present	SJRCD
3	Piney Hollow	118	1993-present	SJRCD
4	South Harrison Township	156	1993-present	SJRCD
5	Hammonton	69	1994-present	SJRCD
6	Atlantic County Utility Authority	41	1994-present	SJRCD
7	Howell	10	1998-present	SJRCD
9	Erail/Berlin	158	1994-present	SJRCD
10	West Cape May	16	1996-present	SJRCD
11	Cape May Courthouse	24	1996-present	SJRCD
12	Dennis Township	16	1996-present	SJRCD
13	Stow Creek	15	1998-present	SJRCD
14	Toms River	3	1998-present	SJRCD

Appendix 2. Example water budget for a hypothetical wetland mitigation site in central New Jersey.

The following example of a water budget for a proposed wetland mitigation site in New Jersey represents a hypothetical but realistic scenario. The purpose of the example is to show some of the typical steps involved in creating a wetland water budget. The numbers used may not be indicative of actual field conditions, but serve as a means to show the process of creating a water budget.

Site Description: The prospective wetland mitigation site is located in the Inner Coastal Plain sub-province, approximately 6 miles east of Hightstown, Mercer County. The site is situated on an agricultural field along the northern boundary of the Millstone River and is 10 acres in size. The site overlies an unconfined aquifer. The native soil onsite is very permeable and the water table is near land surface, so water loss due to infiltration will be minimal. The gradient and soil type are uniform throughout the site so there is only one section of flow, which is 660 feet wide. The upland contributing area, which is 15.1 acres in size, is composed of silty clay loam soil and has an overland cover that is predominantly woods. The plan is to construct a depressional wetland by removing soil from the mitigation site. The primary source of water to the wetland will be ground water, but the site will also receive input from precipitation, non-channelized runoff (from the upland contributing area), and overbank flooding (from the Millstone River).

After examining the locations of data-collection stations in the NRCS's WETS network, it was determined that the closest station to the mitigation site is Hightstown 2W, where there is a 70 percent probability that the growing season is from April 6th to Nov. 1st (209 days).

Computing Water-Budget Values

Precipitation (P)

Steps:

1. Determined that the closest weather station (Figure 8) that would most closely represent precipitation values at the mitigation site was Hightstown, NJ COOP ID 283951. Data for this station are available from the NCDC for a complete period of record, 1948-present (2007).
2. Examined precipitation data for the period January-June, as well as annual precipitation values, and subsequently determined that the years 2005 (average), 1983 (wet), and 1995 (dry) were suitable as the model years. In 2005, January-June precipitation was 20.68 in.; in 1983, it was 32.22 in.; and in 1995, it was 14.63 in. These years also represent average, wet, and dry years in terms of annual precipitation.
3. Obtained daily values for the selected years from the NCDC's web page (Table 3-1).

(Although daily values were obtained, only monthly values of budget terms are listed for this example for brevity.)

Table 3-1. Summary of daily precipitation values for Hightstown 2W station (inches).

Month	Average year (2005)	Wet year (1983)	Dry year (1995)
January	3.65	3.14	3.02
February	2.08	2.55	2.42
March	3.51	8.01	1.92
April	3.79	8.27	1.71
May	3.50	6.20	3.66
June	4.15	4.05	1.90
January-June total	20.68	32.22	14.63
July	4.77	2.34	4.36
August	2.07	4.30	1.72
September	1.53	3.24	5.75
October	11.96	4.64	5.72
November	3.50	6.13	5.46
December	2.95	7.75	2.43
Yearly total	47.46	60.62	40.07

Surface-water inflow (S_i)

The proposed wetland site will receive non-channelized flow in the form of runoff from an upland contributing area. The site will also receive channelized flow in the form of overbank flow from the Millstone River. Calculations to compute both the non-channelized and channelized inputs are presented below.

Non-Channelized Flow

Steps:

1. Selected the SCS runoff curve number/TR-55 method to determine the anticipated non-channelized surface water flow input.
2. Determined drainage area to be 15.1 acres.
3. Evaluated drainage area to have a curve number (CN) of 83 based on soil and overland-cover types.
4. Used CN method to calculate daily non-channelized runoff (Q):

$$Q = (P - I_a)^2/(P - I_a) + S$$

5. Determined the potential maximum retention (S) after runoff:

$$S = 1000/CN - 10, \quad CN = 83$$

$$S = 1000/83 - 10$$

$$S = 2.05$$

6. Initial abstraction (I_a) is the amount of water that will saturate the soil before runoff begins. I_a was calculated as:

$$I_a = 0.2S$$

$$I_a = 0.2\,(2.05)$$

$$I_a = 0.41$$

7. If the daily precipitation value was greater than or equal to the I_a value of 0.41, then the daily runoff value was calculated as: $Q = (P - I_a)^2/(P - I_a) + S$

   If the daily precipitation value was less than 0.41, there was no runoff and a value of zero was assigned for the day.

8. For any day in which runoff, Q, occurred, this value (in.) was multiplied by the off-site drainage area (15.1 acres) and then divided by the wetland surface area (10.0 acres) to compute daily values of runoff depth (in.) over the entire wetland area.

9. Runoff values were calculated for each day and then summed to obtain a monthly value (Table 3-2).

Table 3-2. Summary of daily non-channelized runoff values (inches).

Month	Average year (2005)	Wet year (1983)	Dry year (1995)
January	0.20	0.17	0.59
February	0.18	0.50	0.25
March	0.40	1.94	0.37
April	0.59	1.63	0.22
May	0.66	0.71	0.13
June	1.91	0.82	0.00
July	0.86	0.15	0.85
August	0.13	2.29	0.23
September	0.09	0.96	1.16
October	4.49	1.09	1.37
November	0.40	1.63	1.51
December	0.16	1.58	0.07

Channelized Flow

Although overbank flooding from the Millstone River will not be incorporated directly into the water-budget calculation, the elevation of the 6-month stormwater level will be used to evaluate the suitability of the final elevation of the wetland surface. Leaving this component out of the water budget makes the water budget more conservative; any input of water from flooding will be considered a supplemental benefit.

Steps:

1. Collected river geometry data on-site (stream cross-sectional data) and obtained streamflow data (such as low flow, base flow, and peak flows) for use in the HEC-RAS model. Measurements made on-site will be used to calibrate the model as well as confirm model-output elevations.

2. Determined the river low flow to be 1.9 ft^3/s based on the 7-day, 10-year low flow for the USGS streamflow-gaging station located at Millstone River near Manalapan, N.J. (Watson and others, 2005).
3. Base flow at the proposed mitigation site was determined to be 10 ft^3/s based on field measurements and historical USGS data. The river elevation under base-flow conditions is 105 ft above NGVD 29. Water-surface elevations observed during base-flow conditions were entered into the HEC-RAS model.
4. Determined that both the average base-flow and low-flow conditions are completely contained within the river channel based on historical or measured streamflow data and field surveying.
5. Determined the 3-month and 6-month stormflows by extrapolation on a log-log graph from the 2-, 10-, and 100-year frequency storms. The 3- and 6-month floods are of importance to wetland systems because they offer a potential supply of additional surface-water inputs several times a year.
6. Determined that the 3-month storm does not overtop the natural bank elevation of 109 ft above NGVD 29 but that the 6-month storm does.
7. Based on findings in #6, there will be an additional input of water to the wetland approximately twice a year from overbank flooding.

Surface-water outflow (S_o)

Surface-water outflow (S_o) will be controlled by an outlet weir structure such that there is a maximum daily outflow of 3.61 ft^3/s, which is equivalent to 50 in over the area of the wetland. In cases where the water-surface elevation was greater than the elevation of the outlet structure, the value for surface-water outflow was calculated as the difference between the two elevations. If the water-surface elevation was less than the outlet elevation, then the surface-water outflow was set to zero because there is no surface-water outflow. However, if the difference between the outlet elevation and the water-surface elevation had been greater than or equal to the value for the maximum daily outflow (50 in.), then the surface-water outflow would have been set to the maximum daily outflow. The difference would likely never reach this value for the proposed site. The surface-water output was assumed to be zero for the first day.

Table 3-3. Summary of daily surface-water output values (inches).

Month	Average year (2005)	Wet year (1983)	Dry year (1995)
January	0.00	0.00	0.00
February	0.00	0.00	0.00
March	0.00	2.86	0.00
April	0.00	7.96	0.00
May	0.79	3.40	0.00
June	0.87	1.43	0.00
July	2.36	0.00	0.00
August	0.00	0.00	0.00
September	0.00	1.51	0.00
October	14.44	7.80	4.17
November	1.46	6.50	5.72
December	3.85	8.88	2.31

<u>Ground water inflow and outflow (G_i and G_o)</u>

Steps:

1. Installed three wells equipped with continuous recorders for each uniform section of flow (in this case, there was only one section of flow).

2. Determined ground-water altitude (from field measurements made during 2005) at both the recharge side and the discharge side (stream elevation) of the mitigation site.

3. Conducted hydraulic-conductivity tests on-site. Hydraulic conductivity, K, ranged from 0.6 ft/d (2.11×10^{-4} cm/s) to 2.16 ft/d (7.62×10^{-4} cm/s). The average value was 1.21 ft/d (4.27×10^{-4} cm/s).

4. Applied Dupuit's Equation (a form of Darcy's Law specifically for unconfined aquifers) to obtain daily ground-water inflow and ground-water outflow values.

$$q' = ½ K ((h_1^2 - h_2^2)/L)$$

where

q' = flow per unit width (ft^2/d)

K = 4.27×10^{-4} cm/sec (1.21 ft/d)

h_1 = head at the origin (ft)

h_2 = head at L (ft)

For G_i, L = recharge length = 2,300 ft

For G_o, L= discharge length = 50 ft.

5. Multiplied q' by the width of the section of flow (660 feet) to obtain ground-water flow (ft^3/d).

6. Divided ground-water flow values (ft^3/d) by wetland area (ft^2) and converted the resultant daily flow values to in/d (values summed by month in Table 3-4).

A note about step 4: Water-levels in each of the wells were measured at 15-minute intervals with continuous recorders throughout 2005. Because 2005 was one of the selected model years, these water-level measurements were used to compute the ground-water flows for the representative average year (water level corresponds to head (h) in Dupuit's equation and Darcy's Law). The water-level data collected on-site in 2005 also were used, along with water-level data from a representative off-site long-term monitoring well, to develop a correlation equation for water-level fluctuations. This correlation equation, in combination with historical data from the off-site well for the years 1983 and 1995, was then used to estimate daily water-levels for the mitigation site during the representative wet and dry years. The resultant values were subsequently input into Dupuit's equation to estimate daily ground-water flows for these model years (Table 3-4).

Table 3-4. Summary of daily ground-water flow measurements (inches).

	Average year (2005)		Wet year (1983)		Dry year (1995)	
Month	G_i	G_o	G_i	G_o	G_i	G_o
January	7.29	7.43	7.30	7.47	7.28	7.40
February	6.12	6.61	6.14	6.62	6.15	6.57
March	6.81	7.23	6.88	7.22	6.77	7.23
April	6.58	7.03	6.67	7.09	6.57	6.99
May	6.79	6.85	6.88	6.84	6.76	6.84
June	6.51	6.05	6.51	6.08	6.49	5.98
July	6.71	5.91	6.79	6.01	6.69	5.89
August	6.66	5.16	6.71	5.26	6.58	5.01
September	6.31	3.58	6.32	3.01	6.27	3.21
October	6.51	3.29	6.63	3.92	6.49	3.21
November	6.57	6.84	6.70	6.91	6.63	6.83
December	6.82	7.25	6.91	7.36	6.83	7.20

Evapotranspiration (ET)

There are no ET data-collection stations in close proximity to the mitigation site so a meteorological method was used to estimate ET. The Thornthwaite method was used to calculate monthly ET values, whereas, the Hargreaves-Samani method was used to calculate the daily ET values.

Steps:

1. Retrieved mean monthly temperature (°C) values for 2005, 1983, and 1995 from the Hightstown 2W weather station.

2. Calculated ET using the Thornthwaite Method:

   $ET_i = 1.6(10T_i/I)^a$

   where:

   ET_i = potential evapotranspiration for month *i* (cm/mo)

   T_i = mean monthly temperature (°C)

   I = annual heat index = $\sum(T_i/5)^{1.5}$

   $a = 0.49+0.0179I-0.0000771I^2 + 0.000000675I^3$

   For 2005, I = 54.46, a = 1.34.

3. Applied correction factor for the effects of net radiation at latitude 40° as found in Table 3. Corrected ET values are shown in Table 3-5 and Table 3-6.

4. Also calculated daily values using the Hargreaves-Samani method (these values are used later in the example as part of the daily water-budget analysis). The Thornthwaite method was not developed to calculate daily values.

Table 3-5. Values used in the Thornthwaite equation to calculate potential ET for a representative average year (2005).

Month	Temp °C (T_i)	ET (cm)	Sun correction factor (Latitude at 40°)	Corrected ET (cm)	Corrected ET (in.)
January	-1.39	0.00	0.80	0.00	0.00
February	0.83	0.13	0.89	0.12	0.05
March	2.72	0.63	0.99	0.63	0.25
April	11.17	4.19	1.10	4.61	1.81
May	13.61	5.46	1.20	6.55	2.58
June	22.56	10.74	1.25	13.43	5.29

July	24.56	12.04	1.23	14.81	5.83
August	24.50	12.00	1.15	13.80	5.43
September	20.61	9.52	1.04	9.90	3.90
October	12.89	5.08	0.93	4.72	1.86
November	8.78	3.03	0.83	2.52	0.99
December	0.33	0.04	0.78	0.03	0.01

Table 3-6. Summary of potential ET values using the Thornthwaite equation (inches).

Month	Average year (2005)	Wet year (1983)	Dry year (1995)
January	0.00	0.00	0.00
February	0.05	0.02	0.00
March	0.25	0.71	0.85
April	1.81	1.55	1.64
May	2.58	3.09	3.00
June	5.29	4.84	4.83
July	5.83	5.84	5.90
August	5.43	5.33	5.15
September	3.90	3.66	3.48
October	1.86	1.87	2.28
November	0.99	0.86	0.48
December	0.01	0.01	0.00

Calculating and Graphing Monthly Water-Level Summaries

Using the equation $[P + S_i + G_i] - [ET + S_o + G_o] = \Delta S$, the monthly change in water storage indicates when the inputs exceed the outputs. Tables 3-7 through 3-9 show data summaries for each of the model years. The values in these tables are also illustrated in Figure 3-1.

Table 3-7. Summary of daily values for representative average year (2005).

Month	P (in.)	S_i (in.)	S_o (in.)	G_i (in.)	G_o (in.)	ET (in.)	ΔS (in.)
January	3.65	0.20	0.00	7.29	7.43	0.00	3.71
February	2.08	0.18	0.00	6.12	6.61	0.05	1.72
March	3.51	0.40	0.00	6.81	7.23	0.25	3.24
April	3.79	0.59	0.00	6.58	7.03	1.81	2.12
May	3.50	0.66	0.79	6.79	6.85	2.58	0.73
June	4.15	1.91	0.87	6.51	6.05	5.29	0.36
July	4.77	0.86	2.36	6.71	5.91	5.83	-1.76
August	2.07	0.13	0.00	6.66	5.16	5.43	-1.73
September	1.53	0.09	0.00	6.31	3.58	3.90	0.45
October	11.96	4.49	14.44	6.51	3.29	1.86	3.37
November	3.50	0.40	1.46	6.57	6.84	0.99	1.18
December	2.95	0.16	3.85	6.82	7.25	0.01	-1.18

Table 3-8. Summary of daily values for representative wet year (1983).

Month	P (in.)	S_i (in.)	S_o (in.)	G_i (in.)	G_o (in.)	ET (in.)	ΔS (in.)
January	3.14	0.17	0.00	7.30	7.47	0.00	3.14
February	2.55	0.50	0.00	6.14	6.62	0.02	2.55
March	8.01	1.94	2.86	6.88	7.22	0.71	6.04
April	8.27	1.63	7.96	6.67	7.09	1.55	-0.03
May	6.2	0.71	3.40	6.88	6.84	3.09	0.46
June	4.05	0.82	1.43	6.51	6.08	4.84	-0.97
July	2.34	0.15	0.00	6.79	6.01	5.84	-2.57
August	4.30	2.29	0.00	6.71	5.26	5.33	2.71
September	3.24	0.96	1.51	6.32	3.01	3.66	2.34
October	4.64	1.09	7.80	6.63	3.92	1.87	-1.23
November	6.13	1.63	6.50	6.70	6.91	0.86	0.19
December	7.75	1.58	8.88	6.91	7.36	0.01	-0.01

Table 3-9. Summary of daily values for representative dry year (1995).

Month	P (in.)	S_i (in.)	S_o (in.)	G_i (in.)	G_o (in.)	ET (in.)	ΔS (in.)
January	3.02	0.59	0.00	7.28	7.40	0.00	3.49
February	2.42	0.25	0.00	6.15	6.57	0.00	2.25
March	1.92	0.37	0.00	6.77	7.23	0.85	0.98
April	1.71	0.22	0.00	6.57	6.99	1.64	-0.13
May	3.66	0.13	0.00	6.76	6.84	3.00	0.71
June	1.90	0.00	0.00	6.49	5.98	4.83	-2.42
July	4.36	0.85	0.00	6.69	5.89	5.90	0.11
August	1.72	0.23	0.00	6.58	5.01	5.15	-1.63
September	5.75	1.16	0.00	6.27	3.21	3.48	6.49
October	5.72	1.37	4.17	6.49	3.21	2.28	3.92
November	5.46	1.51	5.72	6.63	6.83	0.48	0.57
December	2.43	0.07	2.31	6.83	7.20	0.00	-0.18

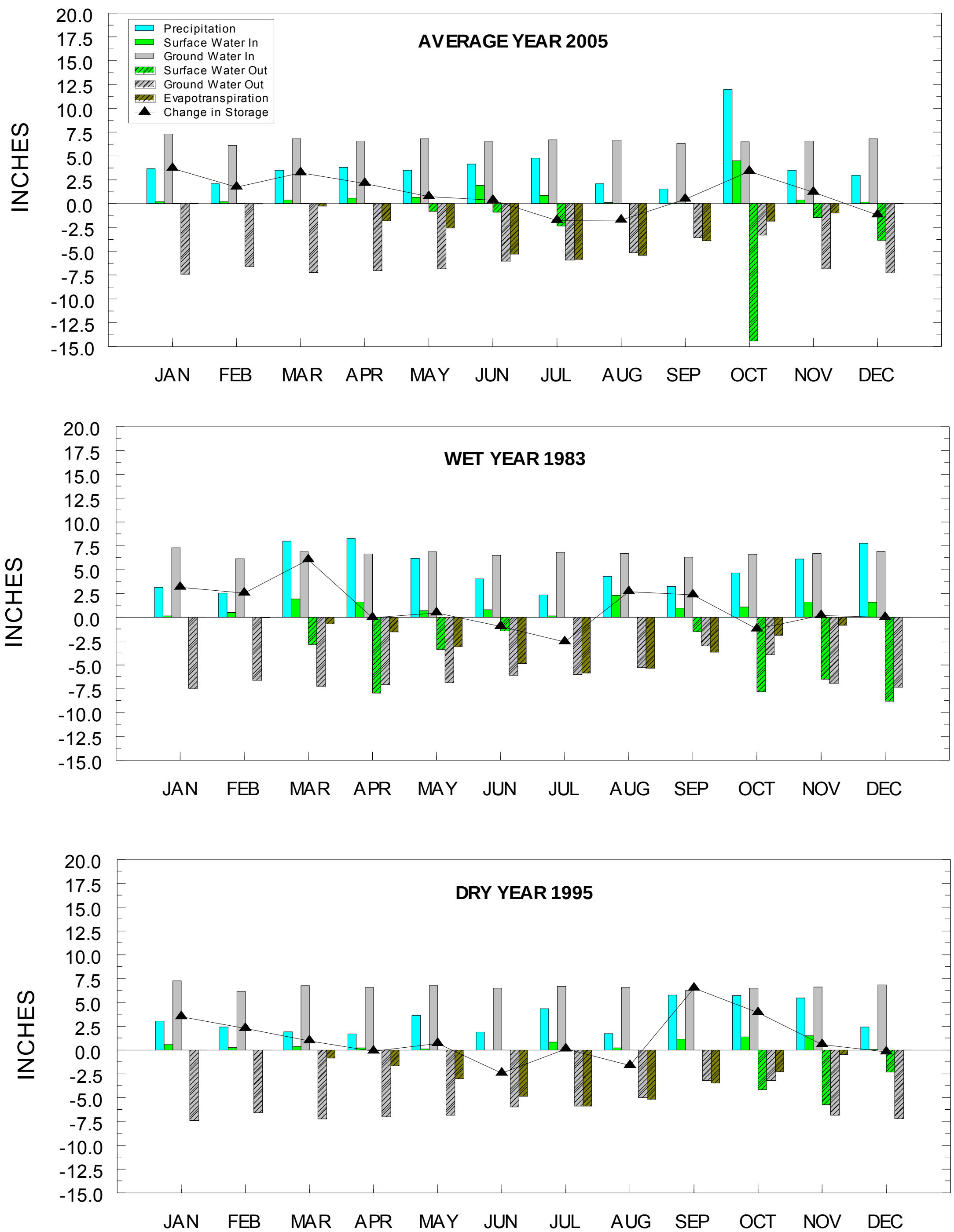


Figure 3-1. Monthly water budgets for the hypothetical wetland mitigation site in central New Jersey for representative average-, wet-, and dry-year conditions.

Summary

The graphs in Figure 3-1 roughly indicate the pattern of the wetland's hydroperiod over a range of conditions. They also show during which months, based on representative data, change in storage is positive and during which months it is negative. Each graph above shows periods of net monthly increases and decreases in storage, with the decreases in storage typically occurring during the summer months. Changes in storage should not be confused with changes in water levels. For example, in the representative dry year (1995), a large positive change in storage occurred in September, but because the change in storage in the preceding months was negative, the water level for September may still be below land surface.

Relating Calculated Daily Water-Budget Values to Ground-Surface Elevation

Water-budget values plotted by month indicate whether there is a net water increase or decrease over a range of conditions. However, in order to assess whether a mitigation site will meet jurisdictional wetland hydrological characteristic requirements, the water elevation at the mitigation site, based on calculated daily water-budget values, needs to be evaluated as well. The following describes how the computed water-budget values can be used to estimate water levels at the hypothetical example mitigation site.

The change in water level on a given day can be estimated by accounting for the net daily inflow or outflow with respect to the conditions estimated for the previous day. Some simplifying assumptions are made regarding site hydraulic properties that control rates of runoff and infiltration. In this example, surface runoff from the site (below a specified daily maximum) and infiltration are assumed to occur within 1 day. The specific yield of the sediments near the land surface is assumed to be 0.25, which is representative of coarse-grained sediments (Fetter, 2001). Also, it is assumed that on each day, one of the following four conditions will determine the water-level change in the wetland as shown in Figure 3-2:

1. If a net increase is estimated and the water level on the previous day is below land surface, then some or all of the increase will saturate some or all of the available pore space and the water table will rise by an amount equal to the net increase, in inches, times the specific yield. If the net increase is sufficiently large, the water level will rise above the land surface.
2. If a net increase is estimated and the water level on the previous day is above the land surface, then the net increase will result in an accumulation of water above the land surface equal to the net increase, in inches.
3. If a net decrease is estimated and the water level on the previous day is below land surface, then the net decrease will result in the desaturation of additional pore space and the water table will decline by an amount equal to the net decrease, in inches, times the specific yield.
4. If a net decrease is estimated and the water level on the previous day is above land surface, then the net decrease will result in a decline in the water level above the land surface by an amount equal to the net decrease, in inches. If the net decrease is sufficiently large, the water level will drop below the land surface.

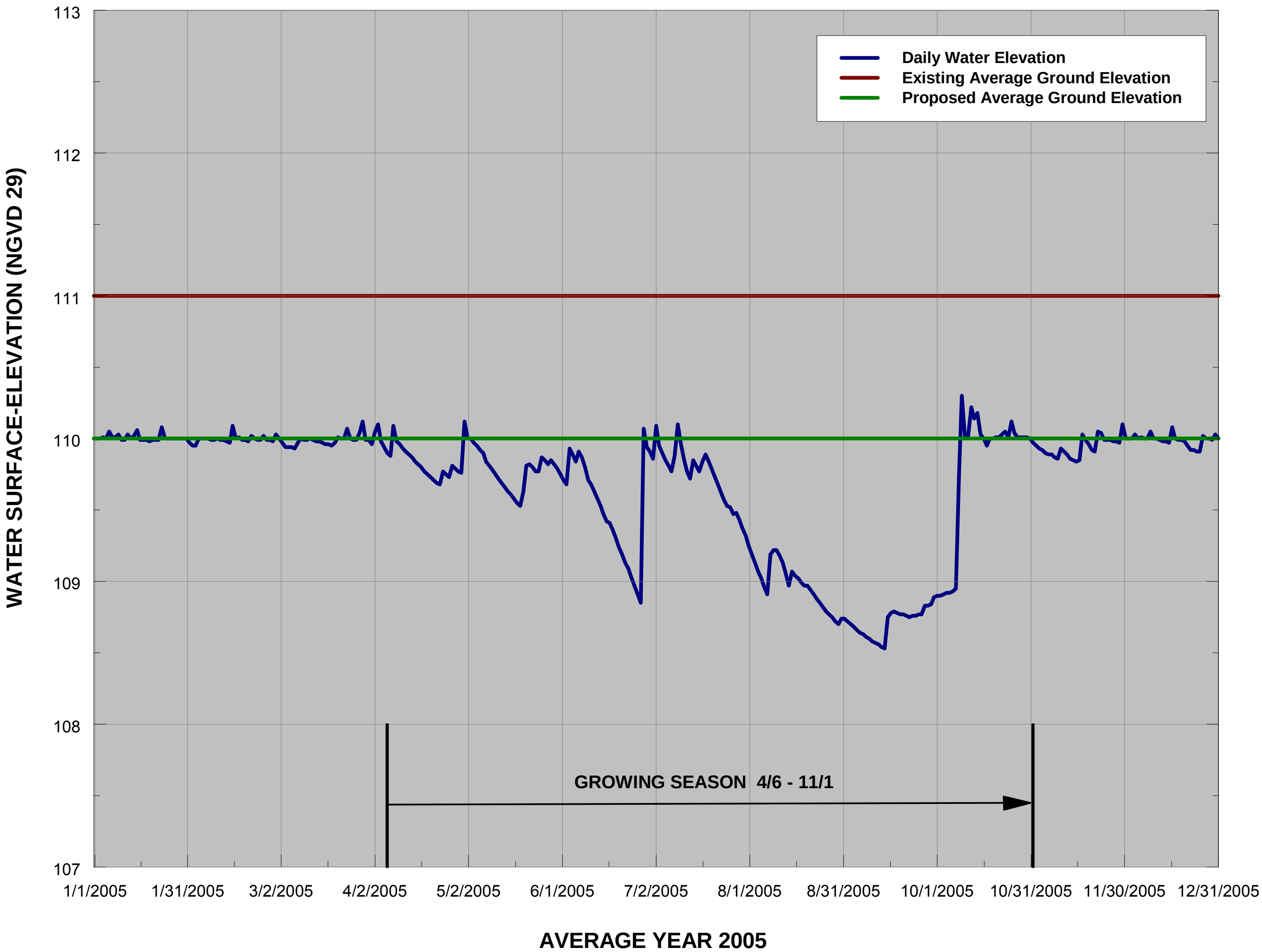


Figure 3-2. Daily water budget for a representative average precipitation year for the hypothetical wetland mitigation site in central New Jersey (wet and dry years not shown).

<u>Summary</u>

Resultant daily water elevations should be above the proposed average wetland elevation for a sufficient period of time during the growing season. According to the USACE 1987 manual, areas that are seasonally inundated and/or saturated to the surface for a consecutive number of days for more than 12.5 percent of the growing season, provided the soil and vegetation parameters are met, are wetlands. As mentioned earlier, at the nearest WETS station (Hightstown 2W) there is a 70 percent probability that the growing season occurs from April 6th to November 11th (209 days). And, as shown in Figure 3-2, the surface of the proposed mitigation site is inundated and/or saturated for approximately 110 days total (52.4 percent of the growing season), based on representative average-year conditions. Of these 110 days, 38 (18.2 percent of the growing season) are consecutive. This meets the USACE's criteria for hydrologic characteristics of a wetland. For this example a capillary fringe length of 4 inches was applied; this is a conservative estimate for coarse sand, based on Fetter (1994). Figure 3-2 shows that the proposed wetland site is likely to have an adequate supply of water during the growing season based on data from a representative average year.

Sensitivity Analysis

A sensitivity analysis was conducted in which values of the water-budget input variables were varied over a reasonable range to determine which parameters account for most of the uncertainty in the water budget. The water-budget components are equally weighted in the water-budget equation; therefore, a simple comparative examination of the likely magnitude of uncertainty in each component can provide a useful indication of this sensitivity. In the following discussion, the likely magnitude of uncertainty in the components is estimated and compared.

Precipitation

Precipitation data from two additional weather stations (Table 3-10) in close proximity to the Hightstown weather station were used to evaluate the variability (or difference) in precipitation amounts between stations. The calculated differences (Table 3-11) indicate the likely magnitude of the differences between precipitation at the two additional sites and at the field site. The difference in precipitation amounts between sites represents heterogeneity in precipitation and, unless there are geographic or topographic differences between the sites and the nearest weather station, one station is not necessarily better or worse for predicting precipitation than another station.

Table 3-10. Summary of precipitation data for three weather stations (inches).

[--, not available]

	Hightstown 2W			Plainfield			New Brunswick		
Month	Average year (2005)	Wet year (1983)	Dry year (1995)	Average year (2005)	Wet year (1983)	Dry year (1995)	Average year (2005)	Wet year (1983)	Dry year (1995)
January	3.65	3.14	3.02	5.13	3.95	3.13	4.49	4.28	3.34
February	2.08	2.55	2.42	2.53	2.35	3.15	2.33	2.28	2.58
March	3.51	8.01	1.92	5.26	8.41	1.56	5.00	8.53	1.67
April	3.79	8.27	1.71	3.74	9.13	1.72	3.32	9.01	1.63
May	3.50	6.20	3.66	1.65	4.83	2.95	2.94	5.13	2.84
June	4.15	4.05	1.90	2.98	4.94	1.95	5.02	3.15	1.84
July	4.77	2.34	4.36	4.35	3.09	9.10	6.40	1.72	4.22
August	2.07	4.30	1.72	0.57	2.73	0.92	1.16	3.10	1.04
September	1.53	3.24	5.75	3.04	2.93	4.21	2.03	2.83	5.27
October	11.96	4.64	5.72	14.05	5.56	6.56	12.32	4.96	5.33
November	3.50	6.13	5.46	4.94	6.44	5.53	4.11	6.42	5.83
December	2.95	7.75	2.43	3.55	9.89	2.17	3.35	9.91	2.53

Table 3-11. Average difference[1] in precipitation between weather stations (inches).

Month	2005	1983	1995
January	0.99	0.76	0.21
February	0.30	0.18	0.49
March	1.17	0.35	0.24
April	0.31	0.57	0.06
May	1.23	0.91	0.55
June	1.36	1.19	0.07
July	1.37	0.91	3.25
August	1.00	1.05	0.53
September	1.01	0.27	1.03
October	1.39	0.61	0.82
November	0.96	0.21	0.25
December	0.40	1.44	0.24
Average difference	0.96	0.70	0.65

[1] The average difference is calculated as the average of the absolute values of the three differences between stations (A-B, B-C, A-C)

Surface water

Variability in non-channelized surface-water inflow was assessed by changing the curve number used in the runoff curve number method from 83 to 85. This resulted in an average difference in inflow values of 0.18 in. for the average year, 0.26 in. for the wet year, and 0.15 in. for the dry year.

Table 3-12. Summary of surface-water inflow data using two different curve numbers.

	Curve Number = 83			Curve Number = 85		
Month	Average year (2005)	Wet year (1983)	Dry year (1995)	Average year (2005)	Wet year (1983)	Dry year (1995)
January	0.20	0.17	0.59	0.31	0.25	0.75
February	0.18	0.50	0.25	0.23	0.62	0.34
March	0.40	1.94	0.37	0.54	2.40	0.46
April	0.59	1.63	0.22	0.77	2.08	0.28
May	0.66	0.71	0.13	0.79	0.96	0.19
June	1.91	0.82	0.00	2.15	1.03	0.01
July	0.86	0.15	0.85	1.08	0.24	1.07
August	0.13	2.29	0.23	0.18	2.58	0.30
September	0.09	0.96	1.16	0.13	1.15	1.49
October	4.49	1.09	1.37	5.23	1.29	1.71
November	0.40	1.63	1.51	0.56	1.97	1.80
December	0.16	1.58	0.07	0.25	1.99	0.11

Table 3-13. Average difference in surface-water inflow values based on varying curve numbers.

Month	2005	1983	1995
January	0.11	0.08	0.16
February	0.05	0.12	0.09
March	0.14	0.46	0.09
April	0.18	0.45	0.06
May	0.13	0.25	0.06
June	0.24	0.21	0.01
July	0.22	0.09	0.22
August	0.05	0.29	0.07
September	0.04	0.19	0.33
October	0.74	0.20	0.34
November	0.16	0.34	0.29
December	0.09	0.41	0.04
Average difference	0.18	0.26	0.15

Ground water

Calculations of G_i and G_o in the initial water-budget analysis were based on an average hydraulic conductivity (K) value of 1.21 ft/d. Substituting the minimum and maximum K values measured at the site into Dupuit's equation provided an indication of the sensitivity of the ground-water calculations to variations in K (Table 3-14). The average difference associated with varying K in this example was 0.58 in. for ground-water inflow and 0.38 in. for ground-water outflow.

Table 3-14. Summary of ground-water inflow and outflow values based on varying K values (inches).

	K = 0.6 ft/d		K = 1.21 ft/d		K = 2.16 ft/d	
Month	G_i (in.)	G_o (in.)	G_i (in.)	G_o (in.)	G_i (in.)	G_o (in.)
January	0.23	0.36	0.46	0.73	0.82	0.73
February	0.19	0.25	0.39	0.51	0.70	0.51
March	0.22	0.29	0.45	0.59	0.80	0.59
April	0.23	0.32	0.47	0.65	0.83	0.65
May	0.28	0.42	0.56	0.84	0.99	0.84
June	0.38	0.66	0.76	1.32	1.36	1.32
July	0.37	0.64	0.75	1.28	1.34	1.28
August	0.57	1.10	1.15	2.21	2.06	2.21
September	0.68	1.35	1.37	2.73	2.45	2.73
October	0.43	0.77	0.87	1.56	1.55	1.56
November	0.23	0.33	0.47	0.66	0.84	0.66
December	0.21	0.26	0.42	0.53	0.75	0.53

Table 3-15. Average difference in ground-water inflow and outflow values based on varying K (inches).

Month	G_i (in.)	G_o (in.)
January	0.39	0.25
February	0.34	0.17
March	0.39	0.20
April	0.40	0.22
May	0.47	0.28
June	0.65	0.44
July	0.65	0.43
August	0.99	0.74
September	1.18	0.92
October	0.75	0.53
November	0.41	0.22
December	0.36	0.18
Average difference	0.58	0.38

Evapotranspiration

Table 3-16 shows monthly ET values generated using three different ET methods—Thornthwaite (method A), Hargreaves-Samani (method B), and pan evaporation (method C). Values for pan evaporation were available for only a few months of every year. These values were multiplied by a pan coefficient of 0.7 to obtain the values listed in Table 3-16. Because the number of available pan-evaporation values for the selected years was limited, they are shown only to illustrate how these results differ from those of the other two methods; they were not used in the water-budget analysis. However, a comparison between monthly values for the Thornthwaite and the Hargreaves-Samani methods revealed that values generated using the Thornthwaite method were lower than those produced using the Hargreaves-Samani method by an average of about 1 in. per month (Table 3-17).

Table 3-16. Comparison of monthly ET values (inches).

[Method A, Thornthwaite method; Method B, Hargreaves-Samani method; Method C, 70 percent pan evaporation; --, not available]

	Average year (2005)			Wet year (1983)			Dry year (1995)		
Month	Method A	Method B	Method C	Method A	Method B	Method C	Method A	Method B	Method C
January	0.00	0.72	--	0.00	0.82	--	0.00	0.87	--
February	0.05	1.14	--	0.02	1.08	--	0.00	0.94	--
March	0.25	1.82	--	0.71	1.96	--	0.85	2.38	--
April	1.81	3.75	--	1.55	3.08	--	1.64	3.59	--
May	2.58	4.70	--	3.09	4.84	3.55	3.00	4.79	--
June	5.29	6.03	--	4.84	6.07	4.52	4.83	5.65	3.29
July	5.83	6.02	5.05	5.84	6.80	5.92	5.90	6.36	4.26
August	5.43	5.64	--	5.33	5.80	4.67	5.15	6.08	4.96
September	3.90	4.59	3.50	3.66	4.32	3.64	3.48	3.95	4.08
October	1.86	2.24	--	1.87	2.34	2.03	2.28	2.76	2.72
November	0.99	1.59	--	0.86	1.35	--	0.48	1.17	--
December	0.01	0.80	--	0.01	0.74	--	0.00	0.65	--

Table 3-17. Average difference in ET values between the Thornthwaite and Hargreaves-Samani methods (inches).

Month	2005	1983	1995
January	0.72	0.82	0.87
February	1.09	1.06	0.94
March	1.57	1.25	1.53
April	1.94	1.53	1.95
May	2.12	1.75	1.79
June	0.74	1.23	0.82
July	0.19	0.96	0.46
August	0.21	0.47	0.93
September	0.69	0.66	0.47
October	0.38	0.47	0.48
November	0.60	0.49	0.69
December	0.79	0.73	0.65
Average difference	0.92	0.95	0.97

Summary

The sensitivity analysis revealed that the water-budget calculations were particularly sensitive to ET. One last step that was taken to determine whether the water-budget sensitivity to ET is significant with respect to the performance of the design was to repeat the water-level calculation using ET values that were higher by an amount equal to the difference that was estimated (approximately 12 in/yr, or 0.033 in/d). The change in ET did reduce the percentage of time that the proposed mitigation site was saturated to land surface during the growing season from 38 consecutive days (18.2 percent of the growing season) to 24 consecutive days (11.5 percent of the growing season). It reduced the percentage of time saturated over the entire duration of the growing season from 52.4 percent to 31 percent. Therefore, one conclusion of the sensitivity analysis is that uncertainty in the ET estimates could slightly affect the performance of the design. If this had been an actual site evaluation, additional measures would have been taken if necessary to minimize the uncertainty by examining the accuracy of the methods used and how the values were calculated. If it is not feasible to do more field work and data analysis to minimize the uncertainty, then another option may be to alter the site design (adjust outlet-structure elevation or excavate deeper) to compensate for the additional water that might be lost to ET.

Appendix 3. Summary worksheet for completion of water budget.

Mitigation-site information

Physiographic province ______________________________

Type(s) of wetland to mitigate ______________________________

____

Wetland size (acres) ______________________________

Hydrogeomorphic setting ______________________________

Reference-site information

Wetland type ______________________________

Distance from mitigation site ______________________________

Type(s) of data collected ______________________________

Hydrogeomorphic setting ______________________________

Water-budget information

PRECIPITATION

Weather station ______________________________

Distance from mitigation site ______________________________

Wet year ______________________________

Dry year ______________________________

Average year ______________________________

SURFACE WATER

Non-channelized flow

Method(s) used to calculate ______________________

____

Channelized flow

Input present? (Y/N) ______________________

Method(s) used to calculate ______________________

____

Type(s) of data collected on-site ______________________

____

GROUND WATER

Number of sections of flow ______________________

Total number of wells installed ______________________

Observation period ______________________

Frequency of data collection ______________________

EVAPOTRANSPIRATION

Method(s) used to calculate ______________________

____