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Hydrologic Variability and Change in the New England Region, USA

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HYDROLOGIC VARIABLITY AND CHANGE IN THE NEW ENGLAND

REGION, USA

By

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ABSTRACT

Traditional water resources management aims to ensure the steady and reliable water supply for human uses and maximize the economic benefits by dampening natural flow variability. However, such management practices essentially changes the flow regime in many ways and ecological degradation is one of the obvious consequences of that. Natural functioning and productivity of the native species require enough water flow in the streams and lake levels with sufficient quality. Thus, to protect the natural ecosystem diversity, sustainable water allocation policies have been developed and employed by many societies around the world. "Chapter 587: In-stream Flow and Lake and Pond Water Levels" is an excellent example of proactive management and planning within a water allocation framework in achieving long-term sustainability of water resources in Maine. Success of this water policy largely depends on using a reasonable guide of ranges of hydrologic variability that may occur in the future, as well as updating the policy to reflect changes in water resources from human activities. A primary context

for this work is Maine's newly established water allocation framework, Chapter 587. The focus of this study is twofold: (a) to analyze a multi-century tree-ring based record of droughts in Maine and a framework to estimate watershed-specific drought risk and (b) to understand the recent changes in the streamflow variability across the New England region, with a particular focus on the nature of surface runoff and baseflow relationships.

We use the multi-century reconstructed PDSI record to understand the natural envelope of drought occurrence (severity and duration) in the state of Maine. This work is motivated by the need to augment the scientific basis to support the emerging water allocation framework in Maine, Chapter 587. Through a joint analysis of the reconstructed PDSI and historical streamflow record for twelve streams in the state of Maine, we find that: (a) the uncertainties around the current definition of natural drought in the Chapter 587 (based on the 20th century instrumental record) can be better understood within the context of the nature and severity of past droughts in this region, and (b) a drought index provides limited information regarding at-site hydrologic variations. To fill this knowledge gap, a drought index-based risk assessment methodology for streams across the state is developed.

Considering the importance of baseflow in river and lake stability during the dry seasons, computing the baseflow from total streamflow is another goal of this study. Three different baseflow separation algorithms were applied to thirty-one stream gauges with natural flow systems in the New England region to calculate and compare long-term Baseflow Index (BFI). A new approach is developed to determine trends at different significance level in daily streamflow, baseflow and surface runoff and applied to the abovementioned stations. In addition, clustering analysis is performed based on seasonal

BFI quantiles. This work is a potential tool to support the water managers in decision-making in different water sensitive sectors. An improved understanding of sensitivity and severity of changes in surface runoff and baseflow is certainly important to human and ecosystem use of streamflow. Future changes, if examined in this framework, are likely to allow a reassessment of policy, a great challenge in changing climate.

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Traditional water resources management aims to ensure the steady and reliable water supply for human uses and maximize the economic benefits by dampening natural flow variability. However, such management practices essentially changes the flow regime in many ways and ecological degradation is one of the obvious consequences of that. Natural functioning and productivity of the native species require enough water in the streams and lakes with sufficient quality. Thus, to protect the natural ecosystem diversity, sustainable water allocation policies have been developed and employed by many societies around the world. "Chapter 587: In-stream Flow and Lake and Pond Water Levels" is an excellent example of proactive management and planning within a water allocation framework in achieving long-term sustainability of water resources in Maine. Success of this water policy largely depends on using a reasonable guide of ranges of hydrologic variability that may occur in the future, as well as updating the policy to reflect changes and trends in water resources from human activities. A primary context for this work is Maine's newly established water allocation framework, Chapter

587. The focus of this study is twofold: (a) to analyze a multi-century tree-ring based record of droughts in Maine and a framework to estimate watershed-specific drought risk and (b) to understand the recent changes in the streamflow variability across the New England region, with a particular focus on the nature of surface runoff and baseflow relationships. We use the multi-century reconstructed PDSI record to understand the natural envelop of drought occurrence (severity and duration) in the state of Maine. A new approach is developed to determine increasing or decreasing trend considering the significance level in daily streamflow, baseflow and surface runoff and applied to the abovementioned stations. In addition, clustering analyses is performed based on seasonal baseflow Index and streams are classified into six groups. This work is a potential tool to support the water managers in decision-making in different water sensitive sectors. An improved understanding of sensitivity and severity of changes in surface runoff and baseflow is certainly important to human and ecosystem use of streamflow. Future changes, if examined in this framework, are likely to allow a reassessment of policy, a great challenge in changing climate.

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PDSI: Palmer Drought Severity Index

HCDN: Hydro-Climatic Data Network

USGS: United States Geological Survey

1. INTRODUCTION

1.1. Sustainable Water Resources Planning and Management

In the past two decades many studies have attempted to understand and define "sustainability" in a meaningful manner and lately it has become a buzzword worldwide. However, a clear definition of sustainability has not emerged. The Brundtland Commission's report "Our Common Future" defines sustainable development as actions that meet the needs of the present without compromising the ability of future generations to meet their own needs." In the context of water resources, the American Society of Civil Engineers (ASCE) defines "Sustainable Water Resources Management" with an emphasis on the long-term and present goals. Although there are debates on the definition of sustainable water resources management that exists among different groups, in general, there is agreement regarding an emphasis on future (Loucks, 2000). For example, changing water demand is a key consideration for sustainable societies, and should be an element of any discussion of sustainability. While a characterization of risk and navigating through uncertainties remains a challenge for sustainability, legacy effects in natural systems (due to past management and policy) and current actions have a significant bearing on the trajectory of these systems. Future impact of today's activities and decisions are not really known. A lack of understanding, largely stemming from uncertainties regarding future needs and expected quality of life of future individuals or societies, remains a central challenge in ascertaining the objectives of sustainable water resources management. Although our predictions on future generation and environmental scenarios are ill-defined and uncertain, systematic attempts are necessary to accrue relevant knowledge that enables planning, designs, policies, operational and maintenance

methods with the consideration of sustainability. The complexity of available resources and coupled human-ecosystem needs also lies mostly in its dynamic nature. This is evident from the limited fidelity with which the current generations of model are able to replicate past variability. As a result, understanding and predicting the dynamic behavior of these systems is a significant challenge. Given this daunting perspective, planning and management can benefit from adaptive strategies that accommodate deep uncertainty. To this end, understanding the role of natural and anthropogenic climate variability on water resources on multiple time scales as well as key manifestations of the changing climate, such as increases in the incidence of extreme events, increasing variability on both the short-term and long time horizons is important.

Another important consideration of achieving sustainability in water resources planning and management is the difficulty in characterizing the variability in natural systems and reccurrence period of extreme events. A widely used concept in water resources management is stationarity that states natural systems fluctuate with an unchanging envelope of variability and occurrences of hydrologic extreme events can be well predicted by analyzing historical/instrumental records. However, anthropogenic disturbance is changing the Earth's climate and also altering the mean, and extremes of hydroclimatic events. Flood risk, water supply, and water quality are largely affected by man-made structures, channel regulation, land-cover change, drainage systems etc. as well as some natural variability like slow dynamics of the oceans and ice sheets (Milly et al, 2008). Substantial changes have been found in extremes of precipitation, evapotranspiration, and discharge rates because of human activities. Thus, an excessive alteration in natural variability may weaken the validity of the stationarity concept and

changing statistics of hydrologic variability may render the water resources planning and management strategies suboptimal.

Conventional water resources management aims to ensure the steady and reliable water supply for agriculture, industrial, drinking water system, navigation, and recreational purposes by dampening the natural variability of river basins (Richter et al., 2003). Such water resource management essentially changes the flow regime in many ways and also impacts the availability of water in streams in different seasons. Although some degree of alteration does not jeopardize natural functionality of aquatic ecosystem, an unintended consequence of too much alteration is ecological degradation. Natural functioning and productivity of native species require enough water with sufficient quality to sustain streamflow and lake levels. Acknowledging the importance of healthy freshwater ecosystem diversity in sustainable society, political leaders, local and federal agencies, water managers and researchers are becoming more engaged into finding ways to meet human needs without affecting the natural life-cycle of freshwater ecosystems. The biggest challenge is that of developing and implementing an ecologically sustainable water management plan; one that restricts any withdrawal and diversion of fresh water that may negatively impact the maintenance of primary production, movement of organisms as well as natural cycling of nutrients. This balance between human and ecosystem needs can essentially be achieved by limiting the amount of the water that can be withdrawn or diverted the natural flow variability by diversion. Unlimited fresh water withdrawal can be restricted by application of ecologically sustainable water allocation rule framework. However, a framework is not easy to establish. One key component of it is to define water levels and in-stream flow during low flow seasons and droughts. Since

sustainable water allocation framework is established to achieve long-term ecological protection goals, future water demand, expected changes in hydrology due to anthropogenic activities, changes in frequency, intensity and duration of extreme events (such as, drought, cyclones, floods etc.) also need to be taken into account. Thus improvement in numerical estimates of key aspects of flow variability is important to sustain the undisturbed physical and biological functions of ecosystem. In general, river engineers emphasize key components of flow regimes: such as, wet- and dry-season baseflow, yearly normal flow and low flows, interannual variability as well as extreme flood and drought conditions that do not occur every year, etc. (Richter et al., 2003). The success of the developed water allocation policy will largely depend on capturing the natural variability of regional hydrology and understanding human influence on water resources. A primary context for this work is Maine's newly established water allocation framework, Chapter 587. The focus of this study is twofold: (a) to analyze a multi-century tree-ring based record of droughts in Maine and a framework to estimate watershed-specific drought risk and (b) to understand the recent changes in the streamflow variability across the New England region, with a particular focus on the nature of surface runoff and baseflow relationships.

1.2. Balancing Human and Ecosystems Needs: Chapter 587

From late 1940s in the United States, water management methods are designed to quantity minimum "in-stream flow" to protect the fish population. Over two hundred methods have been being developed by the researchers in past few decades that consider the adverse impact of flow regulations and human activities on river biota. These

methods can be broadly divided into four categories such as: hydrological rules, hydraulic rating methods, habitat simulation method and holistic methods. Arthington et al. (2006) describes the importance of analyzing different components of natural flow variability such as magnitude, frequency, timing, duration, rate of discharge. He also suggested two different ways to set up environmental flow standards. Firstly, some specific rivers have great social, economical or scientific interest and some large river basins are arguably unique. For that specific river system, site-specific benchmarks can be established based on the natural flow variability using the best hydro-ecological knowledge and monitoring the ecological health. Secondly, identification of "classes" based on the key attributes of flow variability and then calibrate the relationships of flow attributes with measurements of ecological health at each stream class. Within a region, the ecological characteristics of all the streams are expected to be relatively similar compared to the streams from other classes.

Maine Department of Environmental Protection (MDEP) has established *"Chapter 587: In-stream flows and lake and pond water levels"* in 2006 a water allocation framework for the state of Maine. This *Chapter 587* has been considered as an excellent initiative towards the long-term sustainability of water resources in Maine. A major goal of this policy is to balance the human and ecological water use by limiting water withdrawals from the natural water bodies for agriculture and industrial purposes, and community use. This policy restricts excessive withdrawals from rivers, streams, ponds, and lakes and supports maintaining both ecosystem and water quality objectives. Thus, minimum river and stream flows and lake and pond water levels was established with a goal to protect natural aquatic life that can be threatened by excessive water

withdrawal. Maine DEP has classified the stream into four different classes, such as AA, A, B and C, with attention paid to Class AA streams for protecting outstanding natural resources associated to it. *Chapter 587* also established "seasonal aquatic base flow" which is the median value for six different seasons: winter, spring, early summer, summer, fall and early winter. "Seasonal aquatic base flow" is calculated using adequate flow records available for a specific water body. By "adequate flow records" Maine DEP means "minimum of 10 years of U.S. Geological Surveys gauging records or other equivalent flow records. Places, where flow records are available for one year, flow records can be extended by using flow records from watersheds with similar hydrological behavior. For an ungauged watershed, flow records can be established by using drainage area adjustment for records from other gauged sites with at least 10 years of available flow records and with a variation of drainage area between the gauged and ungauged site no more than 50%. The established rules in *Chapter 587* are applicable to withdrawals, direct or indirect removal, diversion or use that causes alteration in levels of non-tidal fresh surface waters of the state.

1.3. Drought Definitions and Past Droughts in Maine

Drought is a relative term and its definition varies with the interest of different group of people. While a farmer treats drought a deficit of moisture that hampers the growth of the plants, an economist thinks drought is the shortage of water that adversely affects economic development. To a hydrologist, drought means below-average water levels in lakes, ponds, reservoirs and reduction of streamflow in rivers. Unlike other natural disasters like floods, cyclones, tornados and earthquakes, drought develops slowly

and it remains unnoticed over a long period of time. Thus, drought is the most complex and least understood among all natural disasters (American Meteorological Society, 1997). It draws people's attention only when it covers and affects a large area; however, by that time it become really difficult to organize and maintain mitigation and aid programs. Drought initially causes soil moisture deficit and lowers the groundwater levels that impede the growth of the plants and subsequently lead to the severe damage to agricultural production. A prolonged drought may also dry up riparian areas, harm vegetation, and impose stress on wildlife habitats. It may also cause death of farm animals, reduce or stop the production of hydropower, and adversely impact the human health.

Although drought is a very natural, recurrent climatic phenomenon and occurs almost everywhere, its features largely vary in both spatial and temporal scale. Drought definitions in Libya and Bali, Indonesia are widely used examples of regional variation of droughts. In Libya, if the annual precipitation is less than 180 mm then it is considered as drought, whereas, in Bali one week without rainfall can be considered as drought. Similarly, the impacts of drought also largely vary with the adaptive capacities of the inhabitants of a particular place. Usually meteorological drought is often more useful and is defined based the degree of dryness or severity (compared to "normal" or average amount) and the duration of the dry period. Meteorological drought definition is not uniform and it varies largely from place to place since the precipitation, atmospheric, landscape, land cover and other watershed properties that cause drought also varies from region to region. In Maine, Natural Drought Condition is defined as "moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less."

Palmer Drought Severity Index (PDSI) is the most commonly used index to measure drought conditions and was developed by Palmer in 1965. It takes into account precipitation, local soil moisture, evapotranspiration and prior information of these variables. It measures zero if its normal or neutral condition, measures positive value if the it is wet and negative if it is dry condition. Thus, any PDSI value lower than negative two is considered as drought condition in Maine.

Being as a water-rich state, Maine is never known as a drought-prone region, however, widespread severe drought has occurred in this area. The severe drought in 1960s was occurred throughout the New England region (Leathers et al, 2000). It was less severe in Maine compared to the other New England states. In Maine, It received more attention for it's for its duration than severity. The 1978 drought in Maine was mild, however, the low-flow recurrence intervals reached the 35 years return period levels (Lombard, 2004). A prolonged drought at the turn of the 21st century (1999-2003) exemplified the widespread nature of the statewide socioeconomic impact of drought. Most USGS monitoring wells recorded low groundwater level during this time-period. Maine Emergency Management Agency in 2002 gives an estimate that almost 7% (17,000 wells in total) of the total private wells went dry in the 9 months prior to April 2002 and wells in the central Maine also likely experienced low water levels. USGS Water-Resources Investigations Report 03-4310 says "In 2001, annual 7-day low flows with greater than 100-year recurrence intervals were recorded in central Maine and low flows with up to 75-year recurrence intervals were recorded in coastal areas." Crop loss of $32 million dollars was also recorded. An imbalance between supply and demand of drinking water was revealed during the drought in 2001-2002 in some parts of the state of

Maine. The coastal part of Maine was experienced the greatest stresses with surface water system (Schmitt, 2003). Although it's impacts on ecology was not well understood, it likely adversely impacted the wildlife and aquatic ecosystem.

1.4. Importance of Baseflow Contribution

Baseflow refers to the genetic component of total streamflow that enters into the steams by flowing from the groundwater and/or shallow subsurface water storages. Estimates of amount of baseflow are extremely important to understand the dynamic behavior of groundwater and its interplay with surface runoff. Knowledge of baseflow is also an important consideration during low flow seasons. Groundwater contributions keep the water following in the streams during extending dry season. In addition, watersheds that receive high surface runoff contribution immediately respond to high intensity rainfalls and can cause floods during spring and fall season. Thus, surface runoff dominated watersheds can be vulnerable to both drought and floods during low and high flow seasons respectively. Baseflow can also be a useful tool in assessment of water quality (Eckhardt, 2008), estimation of groundwater recharge, evapotranspiration, and aquifer parameters (Riggs, 1963; Trainer and Watkins, 1974; Daniels, 1976; Bevans, 1986; Hoos, 1990; Arnold et al., 1995).

1.5. New England's Seasonal Hydrology and Recent Changes

Changes in temperature and precipitation have significant impact in seasonal streamflow generation in the New England region. General description on New England's hydrology is described below.

1.5.1. Winter Season

New England, especially northern part of this region receives significant amount of precipitation in form of snow. Since temperature remains below the freezing point during most of the time of the day, ground is frozen up to a certain depth, movement of water is slow in streams and rivers and precipitation is stored as snow pack. However, many New England gauges have shown declining ratio of snowfall to total precipitation over 50 years of time period from 1951-2000 (Huntington et al. 20003). This change in snow to total precipitation ratio has significantly potential to cause changes in streamflow generation and groundwater recharge in spring season. According to researchers, increasing snowpack densities (Hodgkin and Dudley, 2006), decreasing snow packs, and decreasing ice thicknesses in rivers are experienced in New England region due to climate change. The strongest declining trends of those hydrologic indices are found in northern, coastal and near-coastal regions in New England.

1.5.2. Spring Season

Temperatures vacillate around the freezing point, especially at the end of spring when temperature increases. Snow starts melting and this plays a critical role in surface runoff generation. Precipitation may fall as rain or snow. Some of the precipitation will directly fall to the ground as direct throughfall. Once the rain or snowmelt has reached the ground it will start to infiltrate the soil surface, except on impermeable areas of bare rock, completely frozen soil or artificial surfaces. The rate of infiltration will be limited by rainfall, evapotranspiration and infiltration capacity of soil. During the spring season, snowmelt typically causes the highest annual streamflow in New England region

(Hodgkins and Dudley, 2006). Spring snowmelt also contributes groundwater recharge (Hodgkins and Dudley, 2006, USGS, 2008), which plays an important role in maintaining the groundwater level in summer. In last thirty years of 20th century significant variation is found in seasonality in Northern New England. Northern and Western Maine, and Northern New Hampshire are experiencing earlier spring up to two weeks. Decrease in ice thickness in rivers and increase in coastal Maine snow density playing significant variation is changing streamflow patterns.

1.5.3. Summer Season

Summer is considered typically as dry period in New England because of low flow and high temperature. A larger portion of the streamflow comes as baseflow. A considerable amount of the precipitation will be intercepted and evaporated from the trees back to the atmosphere. This phenomenon is known as evapotranspiration. Once the rainfall arrives at the ground, it will start to infiltrate the soil surface. Rainfall very rarely exceeds the infiltration capacity of the soil. The evaporation rate from the soils, and all water bodies is higher than any other period because of the higher temperature. Though New England gets only a small number of intense thunderstorms, baseflow, coming from groundwater seepage, helps to maintain the flow into the streams.

Being the lowest flow season in New England, summer is the most critical time period to balance both ecosystem and human needs. During 2001-2002 droughts in Maine, water withdrawal was higher than the safe yield in the coastal regions of Maine and the situation was even exacerbated by increasing water demand stemming from seasonal tourism and development (Schmitt et al., 2008). Increase in temperature causes

degradation in dissolved oxygen (Murdoch 2000) that leads to a stressful aquatic environment for many organisms.

1.5.4. Fall Season

Temperature decreases through the fall and reaches to the freezing point again. Rainfalls with higher intensities are much more frequent in this period. This season includes day-long rain storms along with few hurricanes in September through November. Even after water is intercepted by vegetation, a significant amount of rainfall still reaches the ground. During the summer groundwater table and soil moisture content go down. These reservoirs are replenished in the fall by these rain events. Once the groundwater table regains its previous condition and is saturated, surface runoff begins.

Due to climate change, increasing precipitation has been observed in New England over the twentieth century (Henderson 2000). Henderson (2000) mentions, warm and moist air that is brought by the changing pattern of atmospheric circulation during the month of November are probably responsible for the changing pattern in precipitation. Henderson (2000) also finds that, compared to last 100 years, precipitation increases by 3-4 inches in the Atlantic coast during this season.

1.6. Study Objectives

The dry condition experienced in Maine over 1999-2003 including severe drought in 2001-2002 provides an insight into the vulnerability into Maine's drinking water infrastructure and supply (Schmitt, 2003). Adverse impact on community water suppliers severely (Andrews Tolman, Maine Drinking Water Program, written commun, 2003), 32

million dollar crop loss, reduction of blueberry production by at least 80% percent (Maine Agricultural Water Management Advisory Committee, 2003), decrease in water levels in public wells (Maine Emergency Management Agency, 2002 and Schmitt, 2003) and degradation in drinking water quality (Schmitt, 2003) were noticed. Although its impact on ecosystem was not well understood, the above information implies its detrimental impact of ecosystem was also significant. Proactive planning and management within a water allocation framework is important to establish long-term sustainability. Realizing the importance of its ecosystem, Maine DEP **"Chapter 587"** establishes river and stream flows and lake and pond water levels to protect natural aquatic life and other designated uses in Maine's waters. Excessive water withdrawals from Maine's waterbodies are restricted to maintain both water quality and ecosystem health. However, Maine DEP allows a variance to limits of water withdrawals from surface waterbodies during droughts that is defined as *"moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less"*. While twentieth century instrumental data was used to establish Chapter 587, this streamflow data has limited capacity to capture the long-term variability in Maine's hydro-climate. Median flow for six different seasons, such as winter, spring, early summer, summer, fall and early winter are established as "seasonal aquatic base flow". However, hydrological changes in twentieth century, and linked with ecological systems may impose challenges in successful implementation of "seasonal aquatic base flow levels". We augment the scientific baseline to support the water resources management and the emerging water allocation framework in Maine. The key objectives are:

- To examine the natural envelope of hydroclimatic variability and existence of multi-year droughts in Maine using multi-century reconstructed tree-ring data (Chapter 2);

- To examine the reliability of using twentieth century instrumental data as a baseline of design and implementation of management and policy in water resources systems in Maine (Chapter 2);

- To develop a watershed-specific characterization of the risk for low flows by using high-to moderate correlation and joint relationships between water-year runoff volumes across watersheds and statewide PDSI (Chapter 2);

- To separate the baseflow contribution from the daily streamflow records for sixty years from 1948 to 2007 by using three different baseflow separation algorithms and calculate long-term Baseflow Index (Chapter 3);

- To apportion streamflow, surface runoff and baseflow data in seasons and calculate the yearly median flows in a context of established "seasonal aquatic base flow" in *Chapter 587*. Finally, investigate the trends in seasonal median streamflow, surface runoff and baseflow over the abovementioned sixty years (Chapter 3);

- To investigate the trends in streamflow along with its genetic components even at finer scale (daily trends) to assist the decision-makers who needs information only for a particular time of season. For instance, farmers and irrigators may be interested in a couple of weeks of a spring or early summer for irrigation purposes (Chapter 3);

- To regionalize the stream gauges based on homogeneity of seasonal baseflow 25th, 50th and 75th quantile (Chapter 3).

2. PAST CLIMATE, FUTURE PERSPECTIVE: AN EXPLORATORY ANALYSIS USING CLIMATE PROXIES AND DROUGHT RISK ASSESSMENT TO INFORM WATER RESOURCES MANAGEMENT AND POLICY IN MAINE

2.1. Introduction

Located in the northeastern region of the United States, the state of Maine is known for its abundant water resources. In this "water-rich" state, the average annual precipitation (in its three climate divisions) ranges between 40-46 inches. However, a prolonged drought at the turn of the 21st century (1999-2003) exemplified the widespread nature of the statewide socioeconomic impact of drought, including $32 million in crop losses (Maine Agricultural Water Management Advisory Committee, 2003; Schmitt, 2003). Detrimental impacts of the drought on Maine's natural resources and ecosystems were likely significant, however, not well understood. Focusing events (Pulwarty et al., 2007), such as the recent multiyear drought, provide a window into the vulnerability of Maine's people, ecosystems, and economy to hydroclimatic extremes.

Proactive management and planning within a water allocation framework has been viewed as an important step towards the long-term sustainability of water resources in Maine. To this end, in 2006, the state of Maine completed a nearly decade-long rulemaking process that culminated in the promulgation of a sustainable water use policy (MDEP, 2009). A major goal of this policy is to balance the human and ecological use of water by limiting withdrawals from the water bodies for agriculture and industrial purposes, and community use. A key tenet of this water allocation framework concerns the provision of seasonally varying aquatic baseflows that mimic the natural flow regime

and are likely to support ecosystem function and health. The limits on water withdrawals prevent repeated low flow occurrences stemming from excessive withdrawals, thus supporting both ecosystem and water quality objectives. Maine Department of Environmental Protection (MDEP) Chapter 587 allows a variance from limits on water withdrawal from surface water bodies during droughts, when withdrawals may continue to occur despite unmet water quality and aquatic base flow thresholds. These variances aid Community Water Systems that rely on Maine's rivers and lakes. According to MDEP "***Natural drought condition*** *means moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less* (MDEP, 2009)." While the PDSI threshold of -2 and more, severe droughts have rarely occurred in the 20th century, two considerations that motivate this study are:

1. The range of variability seen in limited-length hydrologic and climate records provide a snapshot (depending on the length of the observational record) of the natural envelope of climate in a particular region; as a result, "hydroclimatic surprises" may occur, especially in cases where the observational record fails to represent the range of variability. Such events can prove to be major detriments to effective implementation of management and policy in water resources systems. In this context, to what extent is the 20th century record of Maine's PDSI consistent with the longer-term variability seen in a multi-century climatic reconstruction? To date, limited examples of use of hydroclimatic reconstructions to inform water policy and management exist (for example, Rice et al. 2009). In this study, we use the reconstructed record of Palmer Drought Severity Index (PDSI), dating back to 1138AD to understand the nature of drought occurrence (severity and duration) in the state of Maine.

2. Given that droughts exhibit substantial spatial and temporal variability, an analysis framework that allows translation of statewide PDSI index to watershed-scale estimates of hydrologic risk are likely to benefit water resources management and decision-making. In this study, we pursue a joint analysis of the historical record of the PDSI and streamflow across Maine and develop a probabilistic methodology to assess local hydrologic risk.

2.2. Background

This section describes the motivation and details regarding the water allocation framework, Chapter 587, in Maine. A limited discussion of the drought impacts on aquatic ecosystems is also presented.

2.2.1. In-stream Flows and Lake and Pond Water Levels standards in Maine

The state of Maine, recognizing the value of its natural resources, has pursued environmental protection efforts in the past decades (UCS, 2007). Many of the statutes that have been enacted by the Department of Environmental Protection (DEP) over the last fifty years acknowledge the importance of natural ecosystems and maintaining water quality of all its water bodies. Recently, DEP developed *"The In-stream Flows and Lake and Pond Water Levels rule"* which established river and stream flows and lake and pond water levels to protect natural aquatic life and other designated uses in Maine's waters (MDEP, 2009). Flow management seeks to provide natural variation of flow (seasonal aquatic base flows, or other seasonally variable flows), thus affording protection to aquatic life resources and maintaining water quality standards. Important considerations

such as, alteration of natural flow or water levels (non-tidal fresh surface water) through direct or indirect withdrawal, removal, diversion or other activity are included (MDEP, 2009). Classified state waters, such as, rivers, streams, brooks, lakes and ponds are included. Knowledge concerning droughts is an important input into the community water resources planning and in the allocation of available water supplies. The Chapter 587 (MDEP, 2009) defines "natural drought condition" as *moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less."* The chapter notes, *"Whenever natural drought conditions, in combination with Community Water System use, cause the applicable instream flow or water level requirements of this chapter to not be maintained, the Community Water System may continue to withdraw water for public need subject to any conditions the Department may impose through the issuance of a variance pursuant to 40 CFR 131.13 (2006). Such variances may last for the duration of the drought condition and shall protect all water quality standards to the extent possible, recognizing the combined effects of a natural drought and the need to provide a safe, dependable public source of water."* Thus, the recent promulgation of the water allocation rulemaking in the state of Maine seeks to incorporate adequate instream flow allocations to support ecosystem services, while meeting the allocation needs for agriculture, municipal and industrial sectors. While this is a significant step that will likely catalyze similar rulemaking in other states, the long-term prospects of desirable outcomes in some respect also hinge upon the hydroclimatic thresholds (for example, PDSI) and variances noted in the rulemaking/allocation framework.

2.2.2. Drought Impacts on Ecosystems

Natural droughts stem from lack of precipitation and result in surface runoff deficits and receding groundwater level (Lake et al., 2008); as a result, have a profound adverse effect on the natural life, such as loss of quality and quantity of native flora and fauna. From a riparian ecosystem health standpoint, the lower levels of runoff impact the lateral connectivity in streams. Shallow areas tend to become riffles and runs (Stanley et al., 1997) and pools form in the deep areas. Thus the longitudinal fragmentation constrains the movement of nutrients, planktons, fishes, and other aquatic species. Species with sedentary lifestyles and limited capacity for movement suffer high mortality by getting trapped in riffles; however, pool dwellers survive with little mortality (Golladay et al. 2004, Lake et al. 2008). Mobile species, such as fish and other invertebrates may move into the pool (Magoulick, 2000; Lake, 2008) or as drought develops may emigrate into upstream or downstream reaches of the river based on the landscape of drought progression. In pools, large populations reside in small amounts of water. High concentration and density of different species may increase the intra- and interspecies interaction, such as predation and competition (Lake et al., 2003). Due to disruption of longitudinal flow, transport of nutrients and other organic matter deceases significantly (Dahm et al., 2003). Additionally, standing water in the pools may lead to algal blooms (Freeman et al., 1994; Dahm et al., 2003) with resulting stresses on oxygen availability in pools. In this manner, high density, crisis of food availability, warm temperature, and low oxygen level creates unhealthy and inhospitable condition in the water and may lead to diminishing fish populations and those of other invertebrates (Lake, 2003). During extended droughts, due to the deficit of rainfall, many small

streams and tributaries of large rivers dry up. In temperate climates, reproduction of fish that use small gravel streams for breeding decreases significantly (Lake et al., 2008). Overall, droughts can have a strong detrimental impact on the aquatic ecosystems; thus, a detailed characterization of their frequency and intensity is likely to aid improved management and policymaking to support ecosystem services.

At a location, a definition for natural drought is complicated by the very nature of its severity and duration; at the same time, drought characterization is important for policy setting in water-sensitive sectors. PDSI is a widely used index for drought monitoring and characterization. Efforts to provide regular updates and forecasts for PDSI and other related variables appear to be a key priority for the National Integrated Drought Information System (www.drought.gov) in the United States, and have the potential to inform water allocation and use. An example of the use of PDSI information is that of the natural drought threshold used in Maine's Chapter 587. The analyses presented in the following sections explore the variations in the frequency of natural drought over the past centuries (based on the reconstructed PDSI), incidence of multiyear droughts, and how the 20th century record fits into the drought statistics based on a eight century-long record. Furthermore, we explore the relationship between the PDSI index for the entire state (or a sub-region) and the individual streams that: a. exhibit differing sensitivity to drought stress, and b. represent watershed units where community-scale water management and decision-making is pursued. The aspiration to utilize a reconstructed PDSI records promises significant, new information to inform water resources management and policy. However, comparisons between reconstructed PDSI and the 20th century observations would only be valid if the reconstructions were perfect.

That is, the tree-ring width variations have a one-to-one correspondence with the PDSI variability. As is well known, that is never the case. Environmental proxies (in this case, tree-rings) explain only a portion of the variance of the historical data. This raises an important concern regarding careful interpretation and framing of the insights gained from various analyses in a manner that promotes appropriate use of the new information. Consequently, the use of such information may be limited to qualitative assessment and discussion regarding various management and policy options. To this end, the next section provides a detailed description and discussion of the reconstruction and the range of factors that influence these proxy records.

2.3. Data

Sources, accuracy and reliability and few other descriptions regarding the data used in this study are provided below.

2.3.1. Reconstructed Palmer Drought Severity Index

In this study, we used Cook et al. (2004) reconstructed record of PDSI for the state of Maine dating back to 1138 AD. The Palmer Drought Severity Index (PDSI) has been the most commonly used and most effective drought index in the United States (Palmer, 1965). PDSI reflects variability in precipitation, air temperature, and local soil moisture, along with prior information of these measures, to determine the dryness or wetness of a particular region. PDSI value generally varies from -6 to +6. Zero value is considered as normal or neutral condition. Drought severity is represented as: moderate drought (-2), severe drought (-3), and extreme drought (-4).

In the recent years, tree-ring based reconstructions of the streamflow in semi-arid regions have provided important details to support water resources management (for example, Woodhouse and Lukas, 2006). The availability of water in arid or semi-arid regions is well captured by tree-ring growth. In moist and wetter climates, tree-rings are less sensitive and sometimes the growth is not limited by the moisture conditions; however, while calibrating tree ring data to measured PDSI, nearly half of the hydrologic variability of Maine's PDSI was explained by the tree-ring for years 1928-1978 (data sources, description and quality are discussed in the next section). Normally, wide rings and narrow ring widths correspond to above and below average rainfall respectively. Cumulative precipitation shows high correlation with annual streamflow and also exerts a strong influence of tree-ring growth.

2.3.2. Reliability of the Reconstructed PDSI Data

Although the proxy records provide a general history of drought variability in Maine, one might question the fidelity of the reconstructed PDSI data based on tree-rings. To this end, Cook et al. (2004) use a suite of statistical metrics to verify the association between the actual and estimated PDSI. The updated version of PDSI datasets (available online at: www.ncdc.noaa.gov/paleo/pdsidata.html; Reconstruction of Past Drought Across North America from a Network of Climatically Sensitive Tree-Ring Data) contains a network of 286 grid points (in 2.5° X 2.5° grids) over North America for both instrumental and reconstructed data. We use the grid point number 270 in our analysis. Cook et al. (2004) provide calibration/verification statistics such as: Calibration R^2, Verification R^2, Verification reduction of error (RE), and Verification coefficient of

efficiency (CE). The common time period between the chronologies and instrumental PDSI records were divided into two time series: (a) the years 1928-1978 were used to calibrate the model and, (b) the years 1900-1927 were for reconstruction verification. Calibration R^2 and Verification R^2 measure the percent PDSI variance in common between actual and estimated PDSI at each grid point over the calibration period and verification period respectively. These statistics range from 0 to 1.0, where 1.0 indicates perfect agreement between instrumental PDSI and the tree-ring estimates. Lower values of calibration/verification R^2 indicate increasing failure to estimate PDSI from tree-rings. In the case of the provided dataset, the median Calibration R^2 over the entire 286 grid-points is 0.514, indicating that more than half of the PDSI variance is being explained by tree-ring chronologies. Verification R^2 never exceeds Calibration R^2. Here, the median Verification R^2 drops somewhat from the calibration R^2 (as expected) to 0.445. In the case of reconstructed climatic data, such calibrated variance (Calibration R^2) is considered quite acceptable and small differences between the Verification R^2 and Calibration R^2 indicate satisfactory levels of reliability. RE and CE statistics have been used extensively to test the skill of models in meteorological forecasting. RE assesses the skill of the reconstruction within the verification period, in comparison to the estimates in calibration period for the means of the observed data. The basic difference between RE and CE is that CE uses the verification period mean for assessing the skill of the estimates and RE uses the calibration period mean (Lorenz, 1956; Fritts, 1976; Cook et al. 1999; Woodhouse and Brown, 2001). Both RE and CE have a theoretical range of -∞ to 1.0. Positive values indicate that a reconstruction contains some skill over that of climatology. In other words, there is some information in the reconstruction. In this dataset, the

median RE and CE over all 286 grid-points are 0.419 and 0.357 respectively. RE is always greater than CE (Cook et al., 1999). Here both RE and CE are strongly positive which indicates significant reconstruction skill over the PDSI grid. Thus, it is quite evident that overall North American PDSI grid is well calibrated and verified.

The reconstruction performance statistics for the grid over Maine are available separately. For Maine's grid-point (Grid-point no: 270, Latitude: 45.0^o N, longitude: 70.0^o W) Calibration R^2, Verification R^2, RE, CE values are 0.474, 0.244, 0.211, and 0.165 respectively. In dendrochronology, calibrated variance of 0.474 is considered to be reasonably good (explaining almost half of the variation), however, this information must be discussed alongside any analysis and interpretation. Verification R^2 is 0.244 compared to a value of 0.474 in the calibration period. Verification $R^2 > 0.11$ is statistically significant at the 1-tailed 95% level using a 28-year verification period (Cook et al., 2004). Significant positive magnitudes of RE and CE imply meaningful reconstruction skill for the abovementioned grid-point.

While the reconstructed PDSI provides long-term estimates for drought frequency and severity, it is also evident that only a fraction of the observed variance is explained. Given this, a key consideration is to assess how the spatial extent of the droughts varies when a persistent event occurs. The strength and spatial extent of drought signals were examined by correlating the yearly summer PDSI at each grid-point with the yearly summer PDSI for Maine (Grid-point no 270; Cook et al., 2004), over four different 100-year periods (Figure 2.1). The correlation pattern is then mapped out. In a particular century, if a grid-point contains more than 50 missing values for a particular century then that point is not considered for correlation calculation and placed as a gray circle on map.

(a) 1401-1500   (b) 1601-1700

(c) 1801-1900   (d) 1901-2000

Correlation coefficients

+ 1.0-0.8   + 0.6-0.4   - -0.2–0.4   - -0.6–0.8
+ 0.8-0.6   · 0.4-0.2   - -0.4–0.6   - -0.8–1.0
  Insufficient data

Figure 2.1. Test for fidelity of reconstructed PDSI data. Map of correlations between Maine PDSI records and PDSI records for each grid-point in North America in four different centuries: (a) fifteenth century (1401-1500), (b) seventeenth century (1601-1700), (c) nineteenth century (1801-1900), (d) twentieth century (1901-2000). While large-to-small positive and negative signs are indicating high-to-low correlation positive and negative correlation respectively, gray circle are showing insufficient information

An important goal of this investigation is to examine the spatial pattern of the

correlation in the twentieth century when the instrumental data are available, and then

compare it with maps of other centuries when only the reconstructed PDSI data are

estimated. The 20th century correlation map shows that the PDSI grid point for Maine is strongly correlated with its neighboring grid points, especially points in the New England and Middle Atlantic region in the United States and neighboring Quebec, Canada. Strong to moderate correlation coefficients also found in the East Central region; no significant correlations were found for Central and Pacific region. A strong correlation with neighboring grid points is the most significant characteristics of 20th century correlation map—a pattern that is also replicated in the past centuries. However, in 17th and 19th century, this region was more widespread than in 15th century. This implies that the hydroclimatic variability in Maine and its surrounding region shows a distinctly regional character with some variations on centennial time scales. This is also consistent with the notion that persistent and severe droughts are likely to occur on broader spatial scales and that the attendant drought variability in Maine is consistent with the regional-scale variations.

2.3.3. Historical Streamflow Records

Daily streamflow data from twelve stream gauges in Maine, USA are analyzed in this study (see Table 1 for details). Stream gauging stations are selected based on the availability of a serially complete dataset spanning the 1951-2003 period. Daily mean stream flow data are obtained from the U.S. Geological Survey Hydro-Climatic Data Network for the United States (U. S. Geological Survey, 2010). This network includes the gauges whose watersheds are relatively free of human influences such as regulation, diversion, land-use change, or excessive groundwater pumping.

Table 2.1. General Characteristics of selected USGS stream-gauging stations in Maine

Gauge Number	Gauge Name	Area (Sq. km)	Mean Daily Streamflow (m^3/sec)	Latitude (North)	Longitude (West)	Spearman Rank Correlation with PDSI
01010000	St. John River at Ninemile Bridge	3473	66.75	46°42'02"	69°42'56"	0.73
01010500	St. John River at Dickey	6941	134.93	47°06'47"	69°05'17"	0.71
01011000	Allagash River near Allagash	3828	55.10	47°04'11"	69°04'46"	0.66
01013500	Fish River near Fort Kent	2261	41.68	47°14'15"	68°34'58"	0.65
01014000	St. John River below Fish R, at Fort Kent	15317	275.69	47°15'29"	68°35'45"	0.69
01022500	Narraguagus River at Cherryfield	588	13.93	44°36'29"	67°56'07"	0.64
01030500	Mattawamkeag River near Mattawamkeag	3673	75.08	45°30'04"	68°18'21"	0.67
01031500	Piscataquis River near Dover-Foxcroft	772	17.72	45°10'30"	69°18'53"	0.67
01038000	Sheepscot River at North Whitefield	376	7.18	44°13'22"	69°35'38"	0.56
01047000	Carrabassett River near North Anson	914	21.41	44°52'09"	69°57'18"	0.60
01055000	Swift River near Roxbury	251	0.17	44°38'34"	70°35'20"	0.65
01057000	Little Androscoggin River near South Paris	190	3.92	44°18'14"	70°32'23"	0.61

2.4. Drought Variability and Hydrologic Risk in Maine

A brief description of detrimental impact of four years long drought from 1999-2002 is provided below. A framework is developed to calculate "localized drought risk" based on joint probabilistic information of PDSI and streamflow.

2.4.1. Drought in the Twentieth Century

The four year long drought of 1999-2002 was the most severe and damaging over the historical record (Lombard, 2004). The drought episode evolved from "widespread" during the four years period and "severe" in 2001-2002. Lombard (2004) notes that the major impacts of the drought included: *"(1) thirty-five public-water suppliers, including 8 large community systems, were affected severely (Andrews Tolman, Maine Drinking Water Program, written commun, 2003); (2) approximately 17,000 private wells in Maine went dry in the 9 months prior to April 2002 (Maine Emergency Management Agency, 2002); (3) more than 32 million dollars was lost in crops in 2001 and 2002 and some growers of wild blueberries recorded crop losses of 80 to 100 percent (Maine Agricultural Water Management Advisory Committee, 2003)."* The 7-year long, 1963-1969 drought is the most severe case in the historical record in terms of its duration (Lombard, 2004). The 1978 drought in Maine was mild; however, the low-flow recurrence intervals reached the 35 years return period levels (Lombard, 2004). Observational records show that in each case of multiyear drought, only one or at most two years had a PDSI value below -2. However, consecutive dry years with negative PDSI less severe than the -2 threshold have the potential to cause significant damage to agriculture, forest life, mankind and ecosystem. Such droughts, mild yet prolonged, may

have significant cumulative impact, however, do not meet the severity threshold of -2.

Therefore, a detailed characterization of severity and duration of droughts is an important

consideration for adaptive management and policy implementation for future droughts in

the changing climate.

2.4.2 Long-term Drought Variability in Maine

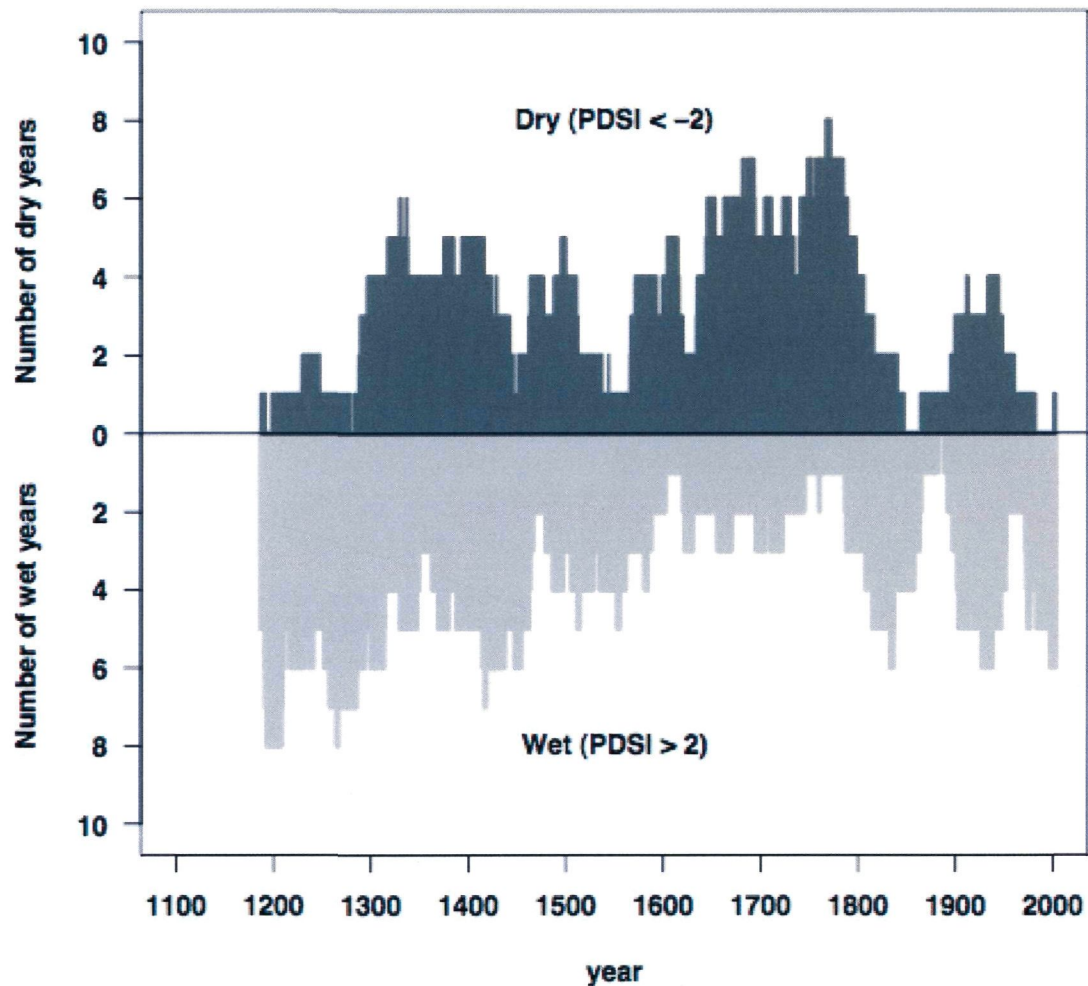**Figure 2.2.** Frequency of dry and wet years. The horizontal axis indicates years from 1138 to 2003 and vertical axis indicates number of wet (in negative direction) and dry years (in positive direction) in every 50-year moving window based on the available paleoclimatic data. This estimate highlights long term variability in climate system and relative "wet" and "dry" conditions in this region. This also shows relative drought

frequencies in different time periods in past millennium and a comparison between droughts in twentieth century to that of other the time periods

Using a fifty-year moving window, we analyzed the frequency of dry (PDSI < -2) and wet (PDSI > 2) years during the 1138 to 2003 period (Figure 2.2). The Fourteenth century was a predominantly wet period. There were only one or two dry years and up to eight wet years were found in every fifty-year period during that time window. But at the end of 13th and in 14th century, frequency of dry years gradually increased and fluctuated between four and six throughout the century. Number of dry years rose during the 17th and 18th century and number of wet years decreased during that time period. Six to eight dry years were observed while one to three wet years occurred during the 17th and 18th century period. Subsequent periods show fluctuations consistent with a variable hydroclimate. Based on the unusually wet and dry year counts, the 20th century PDSI fluctuations in Maine appear to be among the wettest (PDSI > 2) and least dry (PDSI < - 2) compared to the remainder of the multi-century record. This analysis provides an illustrative example of the temporal fluctuations and the dynamic range of drought variability in Maine. Dramatically different wet and dry period frequency in the paleoclimatic record as contrasted with the 20th century instrumental record illuminate the opportunity to use select historical periods are dry, wet, variable, persistent hydrologic regime scenarios that capture a representative set of drought severity and duration statistics. In discussions regarding environmental sustainability, the use of appropriate scenarios is a critical starting point for discussion within a diverse stakeholder setting. Within the context of droughts in Maine, the prospect of using historical drought statistics, appropriately incorporating the uncertainty, and pursuing adaptive management

and options analyses (with water allocation and ecosystems services as the key objectives) can provide valuable insights into the vulnerabilities and also promote proactive exploration of strategies for coping and adaptation.

During the summer 2001 drought period, water withdrawal was higher than the safe yield in the coastal regions of Maine, coupled with an increased water demand stemming from seasonal tourism and development (Schmitt et al., 2008). Proactive planning to mitigate economic, societal and ecosystems impacts resulting from such drought events is critical. On the one hand, the recent drought was a rare event when viewed against the observational record. On the other hand, as seen in the PDSI reconstructions, a scenario where the frequency of natural droughts increases up to six/eight dry years in every fifty years period is likely to have lasting detrimental impacts on communities, ecosystems, and economy.

MDEP recommends negative two or below as the threshold of natural drought condition. Considering this definition, multi-year droughts are rare in the 20th century observational record (Figure 2.3). However, if we consider a less severe PDSI threshold, a number of multi-year dry periods are evident. Taking the -1.50 or below as a threshold, we identified one 4-year, three 3-year and a number of 2-year droughts in this area during the 20th century. Considering -1.00 or below as a threshold, we find two drought events of five years or longer duration, six 4-year drought and large numbers of 3-year and 2-year droughts in Maine. The analysis of frequency and duration discussed above points to the importance of identifying and developing triggers in drought plans that recognize and respond to prolonged moderate droughts (less severe than the natural drought threshold) in a timely manner. In some respect, the above discussion underscores the need to

broaden the definition and metrics for drought monitoring and response. Drought monitoring and forecast products (for example, PDSI or Standardized Precipitation Index) are generally available as area averaged (state or climate division) indices. A related challenge is that of understanding the relationship between the drought indices and the watershed-scale hydrologic variability. The following discussion considers this need and develops an empirical framework that relates PDSI to the streamflow.
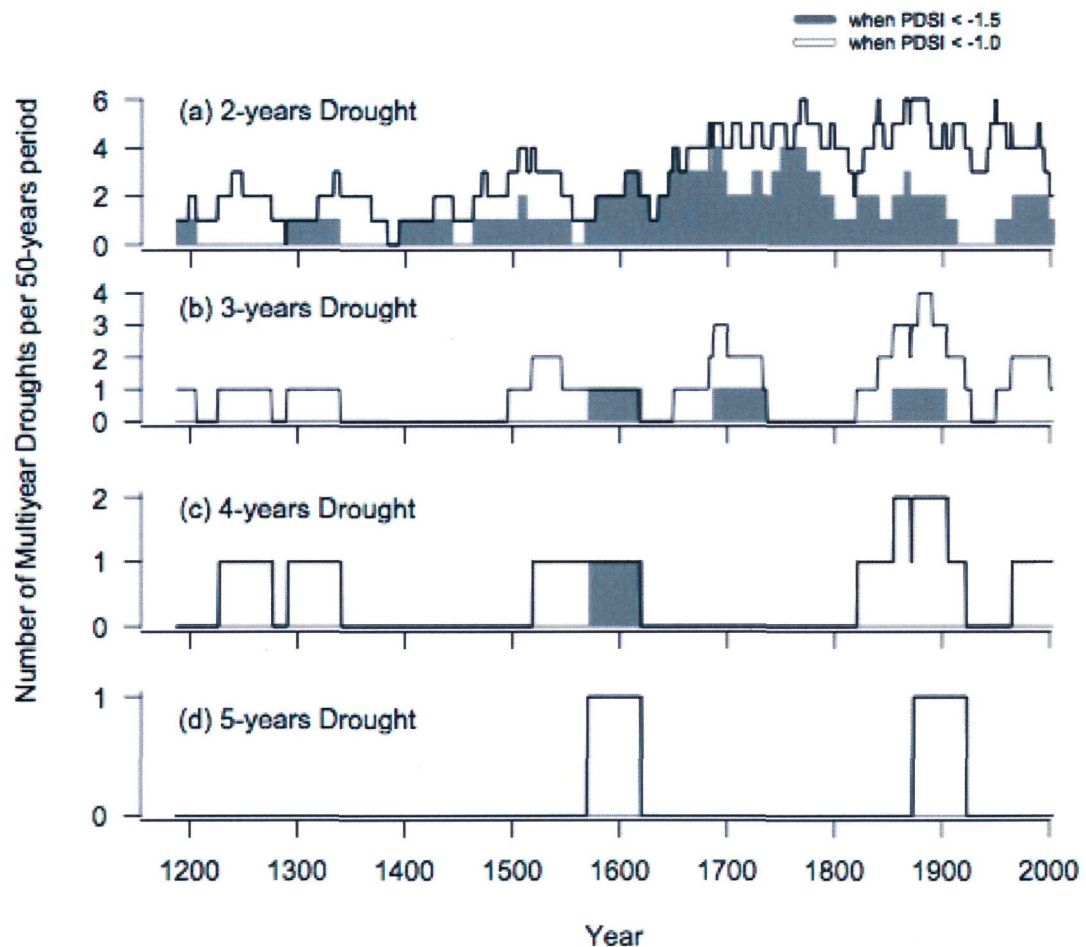
Figure 2.3. Duration of multiyear droughts in long-term paleo-record. Multiyear drought occurrence using a threshold of PDSI below -1.00 and below -1.50 for the paleoclimatic PDSI (1138-2003) and relative change in the multiyear drought frequencies at two

abovementioned thresholds. Drought magnitude is defined as the ratio of severity (consecutive years when PDSI was $\leq$-1.0 or $\leq$-1.50) and duration. Here every event is independent from others. **a.** Shows number of multiyear drought with duration of 2 years, **b.** shows number of multiyear drought with duration of 3 years, **c.** shows number of multiyear drought with duration of 4 years, **d.** shows number of multiyear drought with a duration of 5 years or more.

2.4.3. Ascertaining Local Hydrologic Risk Conditioned on the Statewide Drought Condition

Localized estimates of hydrologic risk, conditioned upon the statewide PDSI observation or forecast, provide usable information to water managers and policy makers. Figure 4a shows the empirical probability distribution for PDSI during three century-long periods. To the extent that PDSI and watershed hydrologic variations are linked, the attendant variability in the PDSI statistics capture the nonstationarity in historical records, also evident in the results from a moving window analysis (Figure 2.2). We used a nonparametric probability density estimation approach to determine the joint probability density of the annual statewide PDSI and mean annual streamflow (1951-2003 period) for the aforesaid twelve stream gauges in Maine. Kernel density estimators represent the non-parametric density estimators that are widely used in theoretical and applied statistics (Bowman and Azzalini, 1997). In comparison to parametric estimators, nonparametric estimators are not restricted to a specified function form, so as to allow adaptive estimation from data, including departures from linearity. The joint nonparametric probability density estimate (statewide PDSI index and the annual streamflow for the St. John River at Ninemile Bridge, Maine stream gauge) for the 1951-2003 period is shown in Figure 2.4b. The strong linear relationship (correlation = 0.73) highlights that the PDSI index is indeed a useful metric to assess broad-scale hydroclimatic variability. However,

the joint relationship also highlights a weakly bimodal nature of the probability distribution, thus providing additional information regarding a flatter probability density distribution for streamflow (Figure 2.4c, unconditional estimate). The correlation of PDSI index with all the stream gauges in Maine is reported in Table 1.
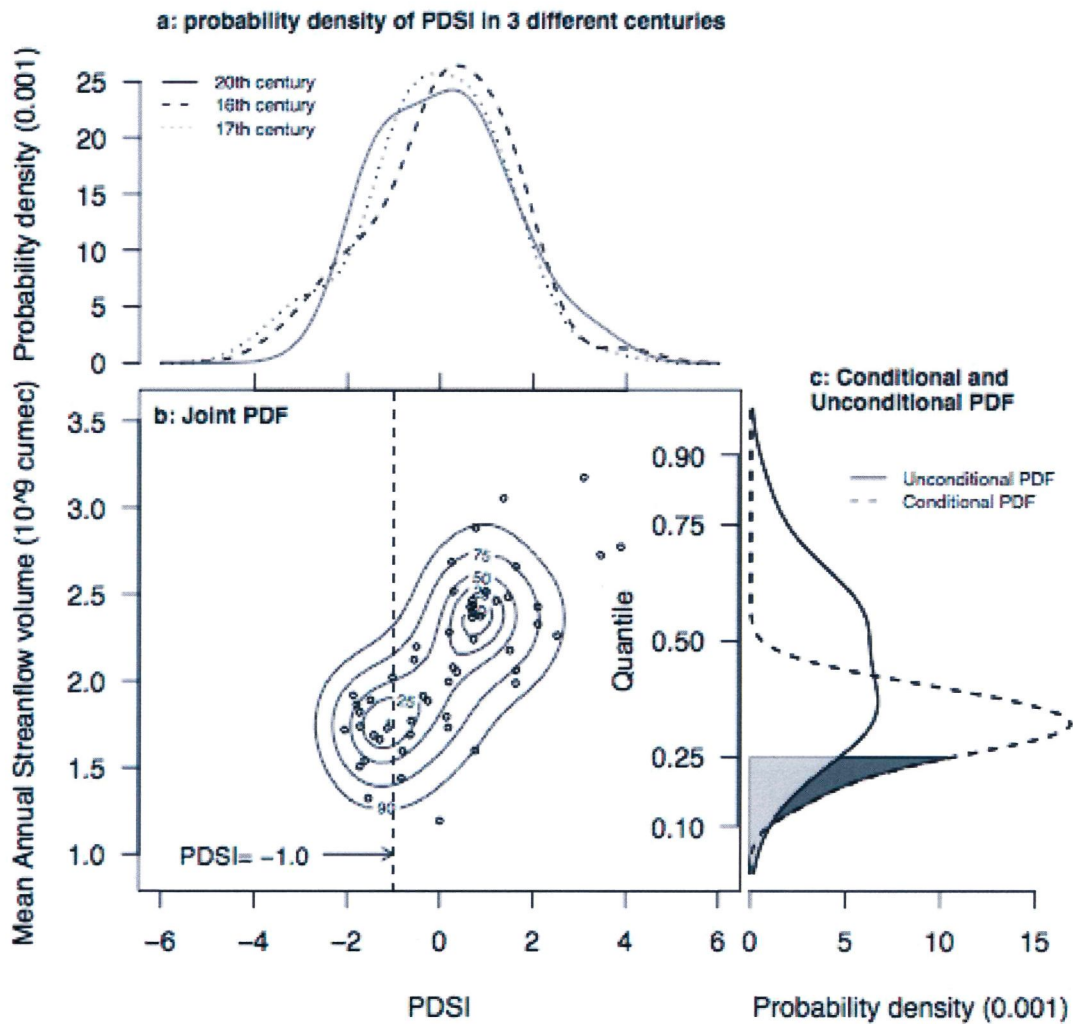
Figure 2.4. Localized "hydrologic drought risk" calculation. **a.** Scatter plot of PDSI and mean annual streamflow (Q) and contour lines in joint probability distribution using Kernel approach, **b.** probability distribution functions (PDF) for unconditional estimate and also the conditional distribution of mean annual streamflow (Q) given PDSI≤ -1 **c.** Probability distribution of PDSI values in three different time periods 1601-1700, 1501-1600 and 1901 to 2000.

Based on the 20th century hydrologic data, we further develop conditional

probability density function between the statewide PDSI and mean yearly streamflows in

different gauges. These relationships are used to develop a watershed-specific

characterization of the risk for low flows. We plotted probability distribution function

(PDF) for all streamflow data of aforementioned gauge with a solid line, Figure 2.4(b).

Then the conditional distribution of mean annual streamflow (Q) given PDSI $\leq$ -1 is

obtained by an appropriate consideration of the joint probability distribution rescaled by

the PDSI probability distribution. Finally, a hydrologic risk estimate is obtained by

considering the ratio of exceedance probability based on the conditional distribution to

that of the unconditional streamflow distribution. Mathematically,

$$Risk = \frac{P((Q \leq Q_{25}) | PDSI \leq -1)}{P(Q \leq Q_{25})}$$

Here, Q is annual stream flow and Q_{25} the 25th percentile based on the historical

record. For a number of stream gauges in Maine, the hydrologic risk associated with flow

occurrences below the 25th percentile of the mean annual flow undergoes a nearly two-

fold increase upon the inclusion of the conditional PDSI information (Figure 2.5). The

results presented in Figure 5 indicate the conditional hydrologic risk for low flows from

watershed-to-watershed. This analysis method allows tailoring of information from

statewide PDSI conditions to a watershed specific risk assessment. If season-ahead

forecast of PDSI are available, then this framework can conveniently translate the

forecast to watershed-specific information.
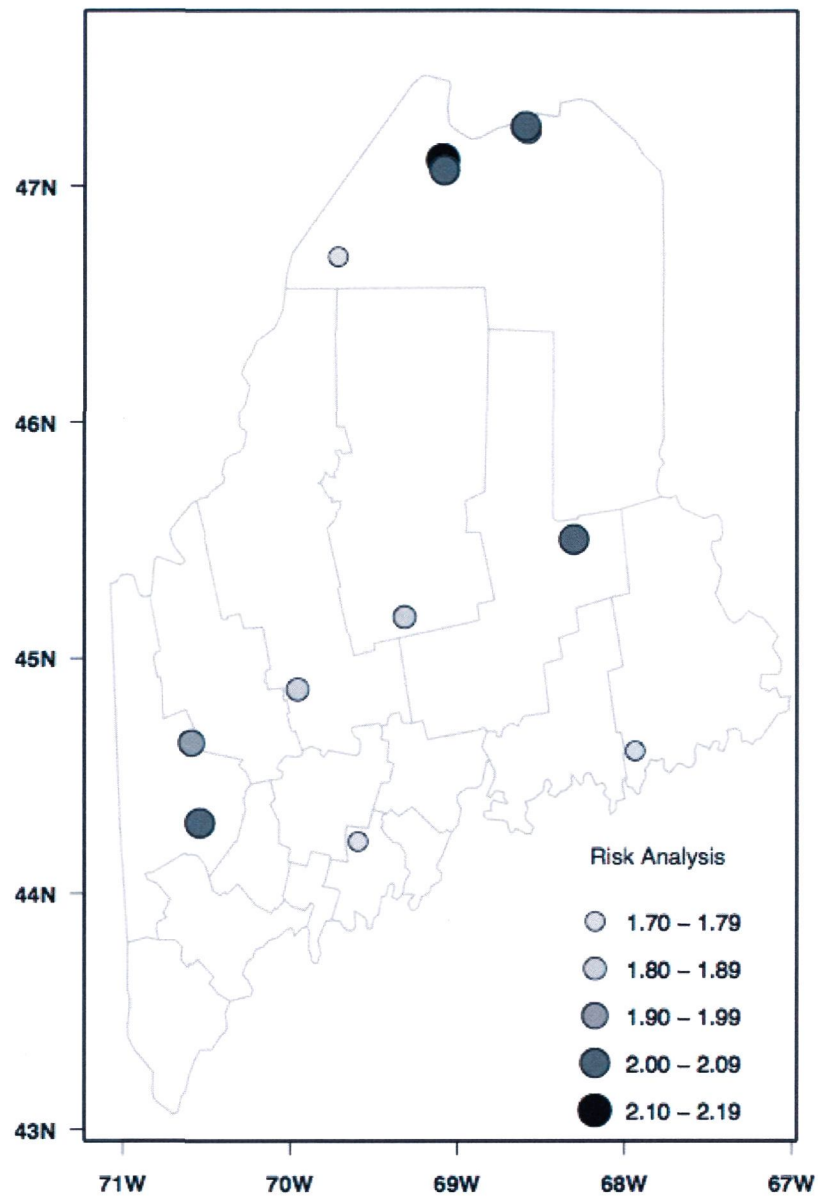
Figure 2.5. Mapping of localized "hydrological drought risk". Ratio presenting the probability for a low flow (lower that the 25th quantile) when PDSI information is included to the unconditional estimate

2.5. Summary and Conclusions

The paleoclimatic reconstructed PDSI record offers the opportunity to analyze the fluctuations in the frequency of wet and dry periods over a multi-century period. A motivating factor for this study is the use of PDSI threshold of -2 in the definition of natural drought for the state of Maine. In this study, we pursued an exploratory analysis of the PDSI index for Maine. We found that the 20th century instrumental record provides important information regarding contemporary drought statistics, including drought events where moderate, yet prolonged droughts have occurred. A multi-century record of PDSI provides an assessment of the broader envelope of hydroclimatic variability in this region, one that is not readily evident in the instrumental record. The historical record provides a number of century-long periods with varying wet and dry period statistics that can be used for scenario analyses and planning. In this study, while exploring the utility of paleoclimatic data we also emphasize the need for a careful consideration of uncertainties regarding use of hydroclimatic reconstructions.

Runoff volumes across watersheds show moderate-to-strong correlation with PDSI. Based on the 20th century hydrologic data we developed joint relationships between the statewide PDSI and water year runoff volume. These relationships are used to develop a watershed-specific characterization of the risk for low flows. These joint probabilistic relationships highlight that the inclusion of PDSI information can benefit local hydrologic risk assessment. Our results suggest the vulnerability of drought (based on statewide PDSI) is not uniform throughout the state, and local characterization methodology shows that elevated hydrologic risk can be quantified for each stream and

emergency management agencies can prepare for droughts based on the higher or lower risk values. Finally, in a changing climate, adaptive management approaches stand to benefit from a careful scrutiny of various aspects of a rule or policy that lends itself to a "set of decisions" to guide the management of natural waters. In increasingly complex and often over-allocated systems, decisions have cascading effects that persist and often have the potential for unintended consequences—consequently, a continual review and, perhaps, inclusion of scientific information is likely to ensure the long-term, intended outcomes for watershed systems.

3. OBSERVED NATURE OF SURFACE RUNOFF AND BASEFLOW IN THE NEW ENGLAND REGION, USA: RECENT CHANGES AND POTENTIAL IMPLICATIONS FOR WATER POLICY

3.1. Introduction

Watersheds having nearly equal area can be very diverse in generating streamflow due to differences in rainfall, climate, geology, wetland properties, soil properties, urbanization and exogenous changes, and land cover. Regionalization of streams is extremely important in regional trend analysis and frequency analysis of floods, low flows and other variables. While constructing any water structure and withdrawing water from a stream, it is important to know baseline hydrology, seasonal variability, flood frequency, flood peaks and low flow indices of that particular stream. Unfortunately, due to limited streamflow data, it is not always possible to understand the hydrologic regime. Then a group of streams with similar flood responses close to that target stream can become a proxy to provide an idea about its properties and facilitates the operation of water resources systems, land use planning and management, bridge and dam construction, flood insurance assessment, protection of populated areas, and solving many other problems. With a goal to assist the water manager for the purposes, classification of the watersheds in New England (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, and Connecticut) into six groups becomes the foremost objective of this paper. Seasonal median surface runoff and baseflow values are the primary focus of this investigation and K-means and hierarchical clustering approaches are applied to group the streams. With the purpose of separating the baseflow component

from total discharge, hydrograph analysis becomes a key component of this study.

Baseflow is a component of total flow in a stream which originates from groundwater and other delayed sources (Hall, 1968). Estimates of baseflow are extremely important to understand the dynamic behavior of groundwater and its interplay with surface runoff. Knowledge of baseflow can be a useful tool in assessment of water quality (Eckhardt, 2008), estimation of groundwater recharge, basin evapotranspiration, and aquifer parameters (Riggs, 1963; Trainer and Watkins, 1974; Daniels, 1976; Bevans, 1986; Hoos, 1990; Arnold et al. 1995). The baseflow Index (BFI), the ratio of the volume of the baseflow to the volume of the total flow for the entire time periods, is an indicator of a watershed's ability to store and release water during the low flow periods (Tallaksen et al. 2004).

To improve the understanding of watershed properties and establishing effective watershed management, numerous baseflow separation methods have been developed. Baseflow estimates vary depending on the choice of methods. To capture this variability, and compare the results baseflow estimates are provided using three widely accepted methods in thirty-one different stream gauges in New England. The primary purpose of this study is to present the spatial variability of BFI values.

Unlike a significant number of individual investigations that were carried out to identify the streamflow changing patterns in North America due to climate change and human influences, this study seeks to develop a statistical framework for determining daily-to-seasonal changing trends of streamflow along with its two genetic components, baseflow and surface runoff, using daily streamflow data. Trends of both daily and seasonal streamflows in conjunction with its two components in thirty-one stream gauges

in New England were estimated. Identification of baseflow trends is important because during the low flow periods flows in the streams mostly depend on baseflow. Thus, the changes in baseflow can significantly impact the quantity and quality of streamflows, plant lives, and aquatic ecosystems of this region. Changing trends in seasonal surface flow also impact the peak floods, especially during the high flow seasons. Understanding of trends in seasonal and daily streamflow components is important for establishing sustainable water resources management in these localities.

Bates et al. (2008) found increases in heavy precipitation is widespread; even places where average precipitation is decreasing. High seasonal variability is found in USA during the warm seasons (Groisman et al. 2004). To make these findings more applicable in different water-sensitive sectors, some relevant research questions are:

(1) Is the increasing pattern in the streamflow the same in New England streams as well, and is the trend the same throughout the year?

(2) If the seasonal trends are fond in any streamflow components, which factors may trigger this?

(3) How do the two components of streamflow interact, and different seasons which component becomes key in observed trends in streamflow?

(4) Is there any regional coherence among the stream trends in surface runoff and baseflow?

3.2. Data and Methods

Daily mean streamflow data from river basins in the New England region of the USA were used for this study. Daily mean stream flow data were obtained from the U.S.

Geological Survey (USGS) Hydro-Climatic Data Network (HCDN) that includes data from 1659 streamflow-gauging stations across the USA. This network includes the gauges whose watersheds are relatively free of human influences such as regulation, diversion, land-use change, or extreme groundwater pumping. Ten gauges/stations/sites from Maine, six from New Hampshire, two from Vermont, four from Massachusetts, four from Rhode Island and five from Connecticut were included for this study. Stream gauge locations are shown in figure 3.1 and general properties (such as, USGS site no, name, latitude, longitude, area) are provided in table 3.1.
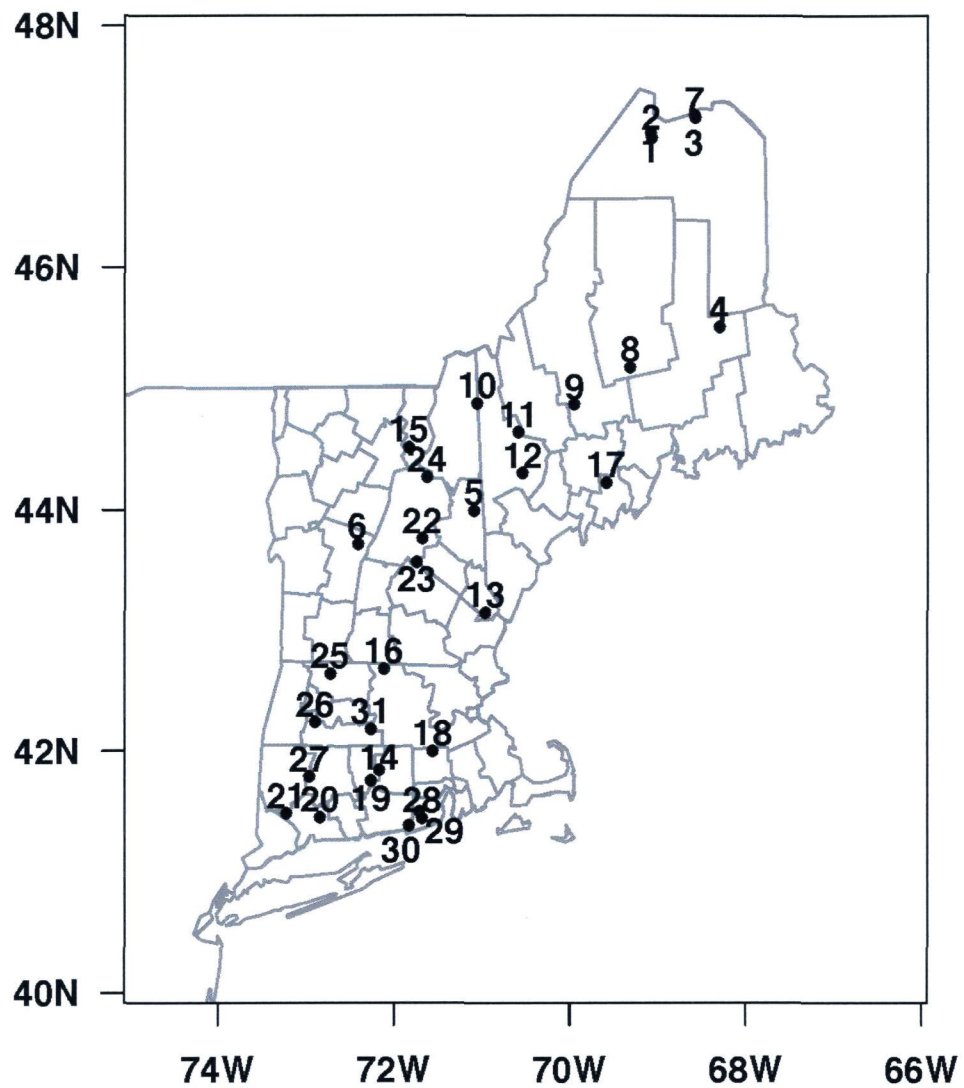
Figure 3.1. Location of the selected stream-gauging stations in the New England region

Table 3.1. General properties of selected stream-gauging stations in the New England

Serial No	Gauge No	Station Name	Watershed (Sq. miles)	Latitude	Longitude
1	01010500	St. John River at Dickey, ME	2,680	47°06'47"	69°05'17"
2	01011000	Allagash River near Allagash, ME	1,229	47°04'11"	69°04'46"
3	01013500	Fish River near Fort Kent, ME	873	47°14'15"	68°34'58"
4	01014000	St. John River below Fish R, at Fort Kent, ME	5,665	47°15'29"	68°35'45"
5	01030500	Mattawamkeag River near Mattawamkeag, ME	1,418	45°30'04"	68°18'21"
6	01031500	Piscataquis River near Dover-Foxcroft, ME	298	45°10'30"	69°18'53"
7	01038000	Sheepscot River at North Whitefield, ME	145	44°13'22"	69°35'38"
8	01047000	Carrabassett River near North Anson, ME	353	44°52'09"	69°57'18"
9	01052500	Diamond River near Wentworth Location, NH	152	44°52'39"	71°03'27"
10	01055000	Swift River near Roxbury, ME	96.9	44°38'34"	70°35'20"
11	01057000	Little Androscoggin River near South Paris, ME	73.5	44°18'14"	70°32'23"
12	01064500	Saco River near Conway, NH	385	43°59'27"	71°05'26"
13	01073000	Oyster River near Durham, NH	12.1	43°08'55"	70°57'56"
14	01076500	Pemigewasset River at Plymouth, NH	622	43°45'33"	71°41'10"
15	01078000	Smith River near Bristol, NH	85.8	43°33'59"	71°44'54"
16	01111500	Branch River at Forestdale, RI	91.2	41°59'47"	71°33'47"
17	01117500	Pawcatuck River at Wood River junction, RI	100	41°26'42"	71°40'53"
18	01118000	Wood River at Hope valley, RI	72.4	41°29'53"	71°43'01"
19	01118500	Pawcatuck River at Westerly, RI	295	41°23'01"	71°50'01"
20	01119500	Willimantic River near Coventry, CT	121	41°45'02"	72°15'58"
21	01121000	Mount Hope River near Warrenville, CT	28.6	41°50'37"	72°10'10"
22	01134500	Moose river at Victory, VT	75.2	44°30'42"	71°50'16"
23	01137500	Ammonoosuc River at Bethlehem Junction, NH	87.6	44°16'07"	71°37'51"
24	01144000	White River at West Hartford, VT	690	43°42'51"	72°25'07"
25	01162500	Priest Brook near Winchendon, MA	19.4	42°40'57"	72°06'56"
26	01169000	North River at Shattuckville, MA	89	42°38'18"	72°43'32"
27	01176000	Quaboag River at West Brimfield, MA	150	42°10'56"	72°15'51"
28	01181000	West Branch Westfield River at Huntington, MA	94	42°14'14"	72°53'46"
29	01188000	Bunnnell (Burlington) near Burlington, CT	4.1	41°47'10"	72°57'55"
30	01196500	Quinnipiac River at Wallingford, CT	115	41°26'58"	72°50'29"
31	01204000	Pomperaug River at Southbury, CT	75.1	41°28'50"	73°13'30"

3.2.1. Baseflow Separation Methods

To assess the robustness of the baseflow estimates, we applied three commonly used methods: the United Kingdom Institute of Hydrology or UKIH method (Institute of hydrology, 1980 and Piggott et al. 2005), one parameter digital filter or BFLOW filter methods (Arnold and Allen, 1999), and recursive digital filter method or Eckhardt method ([1]Eckhardt, 2005). The separation techniques used in this investigation partitions the streamflow into two parts, surface runoff and baseflow, and provides a continuous separation of baseflow from daily streamflow data. Brief description of these procedures is presented below:

3.2.1.1. UKIH Baseflow Separation Method

The United Kingdom Institute of Hydrology or UKIH method is applied to daily average streamflow data in order to find the turning points. The turning points indicate the days and corresponding values of streamflow where the observed flow is assumed to be entirely baseflow (Piggott et al. 2005). To identify the turning points, the streamflow data are partitioned into non-overlapping five-day envelopes. Then the minima of each envelop are chosen, then defined as Q_1, Q_2, Q_3, ... Q_i. then (Q_1, Q_2, Q_3), (Q_2, Q_3, Q_4), ... (Q_{i-2}, Q_{i-1}, Q_i) etc. will be considered in turn. In each case, if $(0.9 \times \text{central value}) < \text{outer values}$, then the central value is a turning point or ordinate for the baseflow line. A daily time series of baseflow can be calculated by applying linear interpolation to the timing of the input streamflow data. Daily streamflow and baseflow are achieved by calculating the volume of water beneath the recorded hydrograph and baseflow line, respectively. Long-term baseflow index (BFI) can be reckoned by dividing the total volume of the daily

baseflow by the volume of the daily streamflow. Mathematically,

$$BFI = \frac{\text{Volume of the total baseflow, } V_{base}}{\text{Volume of the total streamflow, } V_{total}} \qquad (3.1)$$

Surface runoff can be estimated by subtracting the daily baseflow values from the total streamflow. The UKIH method is applied to selected stream gauges in New England (details are described in table1) and one example is shown in figure 3.2 for USGS Gauge no. 01031500 (Piscataquis River near Dover–Foxcroft) for water year 1948.
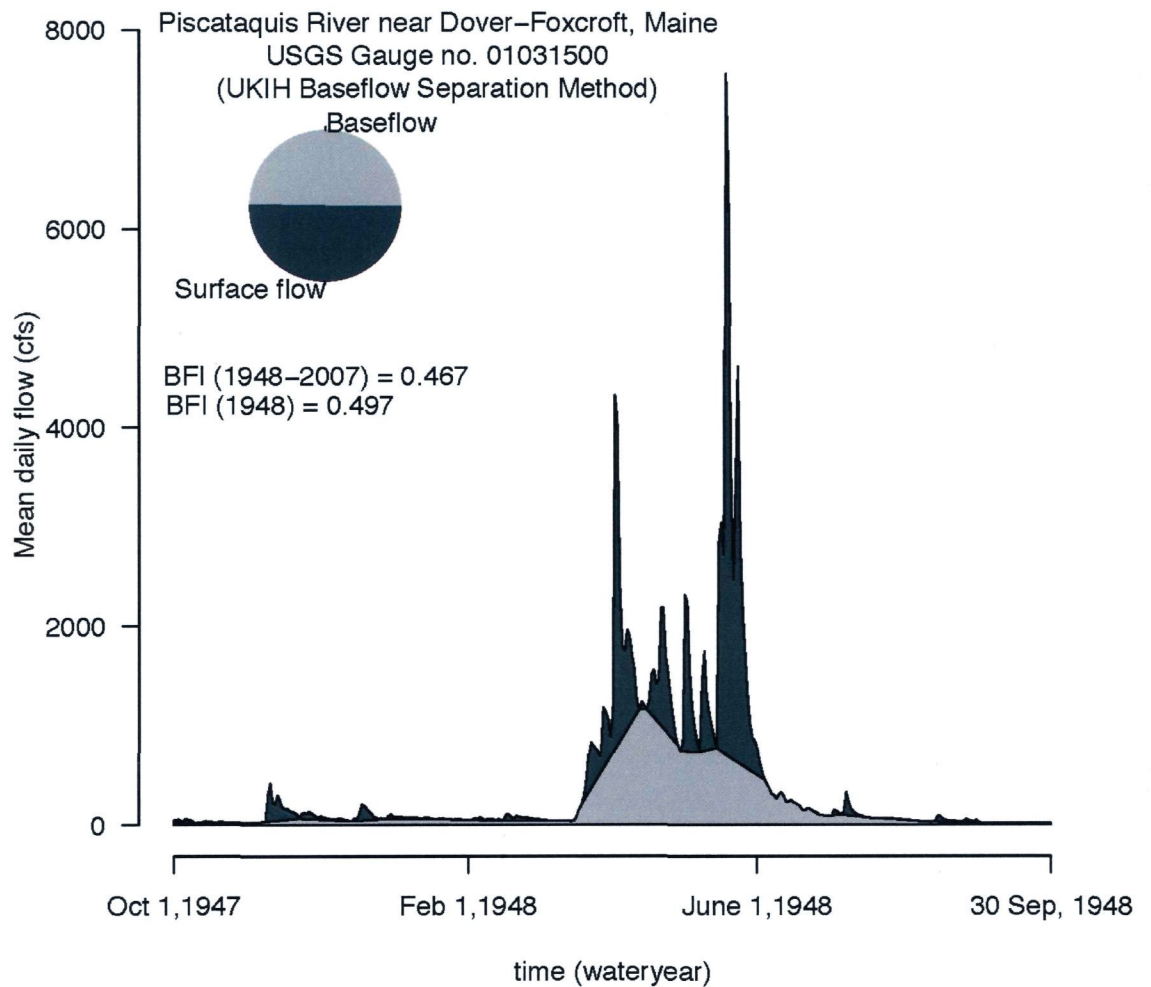
Figure 3.2. Example of UKIH baseflow calculation. Observed streamflow and calculated baseflow using the UKIH method for the Piscataquis River near Dover–Foxcroft, Maine (USGS station no- 01031500) in the water year of 1948. Percentage contributions of surface runoff and baseflow to the total streamflow are shown by a pie-diagram.

3.2.1.2. Recursive Digital Filter Methods

The recursive digital filter was developed by Nathan and McMahon (1990) and modified by Arnold and Allen (1999). This technique was originally used in signal analysis and processing to separate the high frequency component from a signal (Lyne

and Hollick, 1979). Filtering high frequency signals as surface runoff from the low frequency signals associated with baseflow is similar to removing unwanted high frequency waves in signal analysis. Equation (3.2) shows one parameter digital filter for baseflow separation (Lyne and Hollick, 1979; Nathan and McMahon, 1990; Arnold and Allen, 1999; Arnold *et al.*, 2000).

$$q_t = \alpha \times q_{t-1} + \frac{(1+\alpha)}{2} \times (Q_t - Q_{t-1}) \qquad (3.2)$$

In the above equation q_t is the filtered surface runoff at the time step t; q_{t-1} is the filtered surface runoff at the t-1 time step; α is the filter parameter; Q_t is the total streamflow at t time step; and Q_{t-1} is the total streamflow at t-1 time step. Equation (3.2) is sensitive to filter parameter, α and variation in results largely depends on its value. Nathan and McMahon (1990) suggest $\alpha=0.925$ can give reasonable results when compared to manual baseflow separation results, and this value is used in the BFLOW program (Arnold and Allen, 1999) and also as a default value of filter parameter in the automated web GIS based hydrograph analysis tool, WHAT (Lim at al. 2005). An example calculation is shown in figure 3.3 by using the BFLOW method.
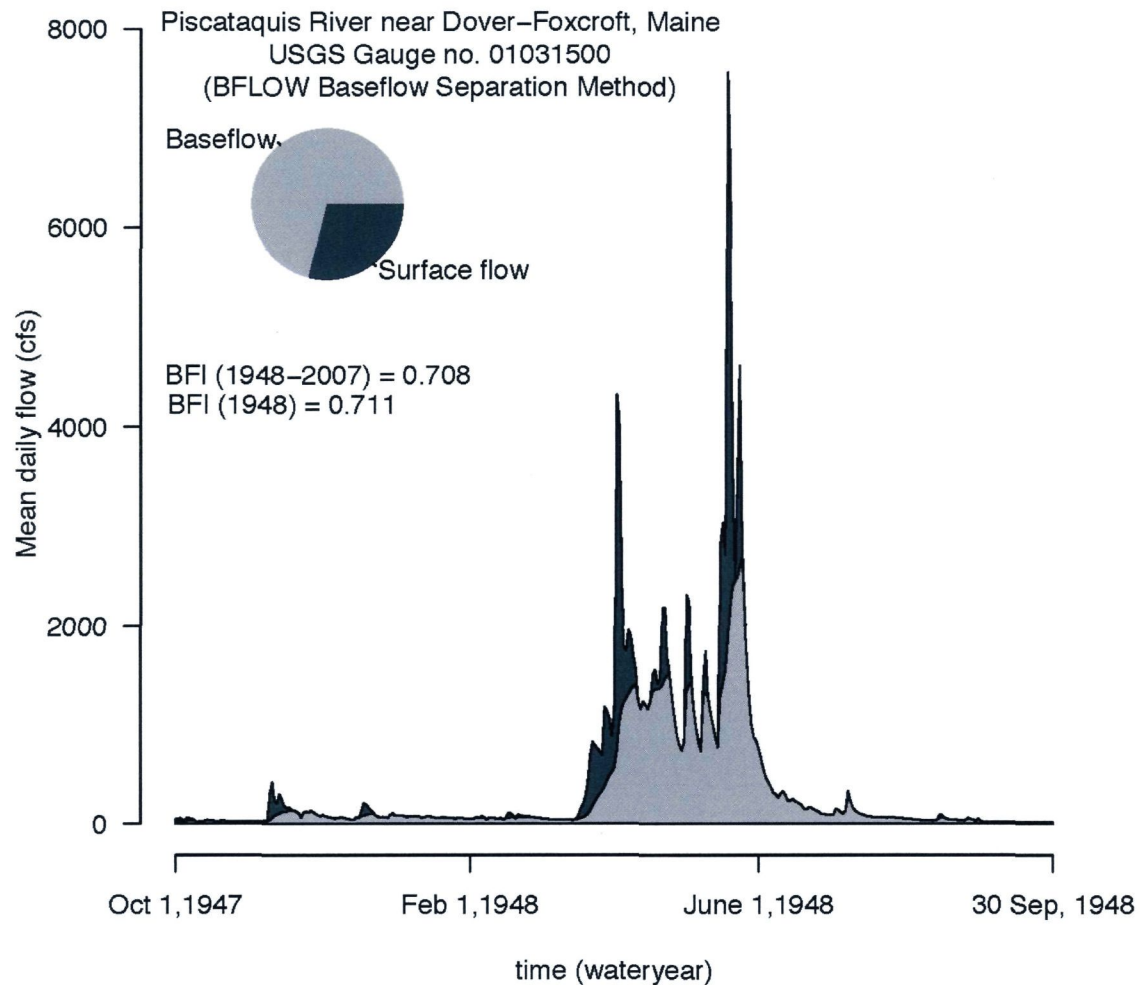
Figure 3.3. Example of BFLOW baseflow calculation. Observed streamflow and calculated baseflow using the BFLOW (one parameter digital filter) method for the same station and year. Percentage contributions of surface runoff and baseflow to the total streamflow are also shown by the pie-diagram.

Chapman (1991) found that this digital filter method estimates constant streamflow and baseflow when the surface runoff ceased and thus results are theoretically incorrect. He developed a new algorithm, which is known as two parameters digital filter method. Eckhardt (2005) establishes a new algorithm (equation 3.3) for baseflow

separation and showed that the Chapman filter is a special case of that.

$$b_t = \frac{(1 - BFI_{max}) \times a + b_{t-1} + (1 - a) \times BFI_{max} \times Q_t}{(1 - a) \times BFI_{max}} \qquad (3.3)$$

Where b_t is the filtered baseflow at t time step; b_{t-1} is the filtered baseflow at the t-1 time step; BFI_{max} is the maximum value of long-term ratio of baseflow to total streamflow; a is the recession constant; and Q_t is the total streamflow at t time step. The major challenge of this algorithm is that its one parameter, BFI_{max} has a large influence on the baseflow separation results and it is non-measurable (Eckhardt, 2005). On the other hand, another parameter, a, has less influence on the results; however, it can be estimated by carrying out a recession analysis. To minimize the subjective influence of BFI_{max} on the baseflow separation, different BFI_{max} values were estimated in different hydrological and hydro-geological situations. Eckhardt (2005) applied and validated his filter approach on watersheds in Pennsylvania, Maryland, Illinois, and also in Germany. Based on the results, he proposed BFI_{max} value of 0.80 for perennial streams with porous aquifers, 0.50 ephemeral streams with porous aquifers, and 0.25 for perennial streams with hard rock aquifers. A river can be considered as ephemeral if it is waterless during 10% time or more of a year; otherwise, it is perennial. From our calculation, it was found that all the selected streams in New England are perennial, so we used 0.80 as the value of BFI_{max}.

The determination of recession constant 'a' is fairly subjective and there are a number of methods available for recession analysis. In his approach [2]Eckhardt (2008) uses the correlation method (Langbein, 1938); and in this study computation of the recession constant is done by using the same approach. Every streamflow value, Q_k that is part of a recession period of at least five consecutive days is taken into consideration.

After determining the recession period, two consecutive days are plotted where first day's discharge data, Q_k is X-coordinate and next day's discharge, Q_{k+1} is the Y-coordinate of a point. Thus all the points of the recession period are plotted. Then an envelope line is plotted along the upper bound of this scatter plot. In this study, a line that goes through the origin was fitted by applying a 95th quantile regression to find the best fit of the upper bound. The recession constant is simply the slope of such a line, which is fitted to the upper bound of the scatter plot. In our research, the value of the recession constant varies from 0.955 to 0.989. While computing the values of recession constant, an important aspect is to note the change of its values over time. As a result, recession analysis was carried out for two halves of the entire data series (first 30 years from 1948 to 1977 and the last 30 years from 1978 to 2007). The difference between these two values was very low. An example of baseflow calculated by the Eckhardt method is shown in figure 3.4 for the same gauge and same year that we used in figure 3.3 and figure 3.4.
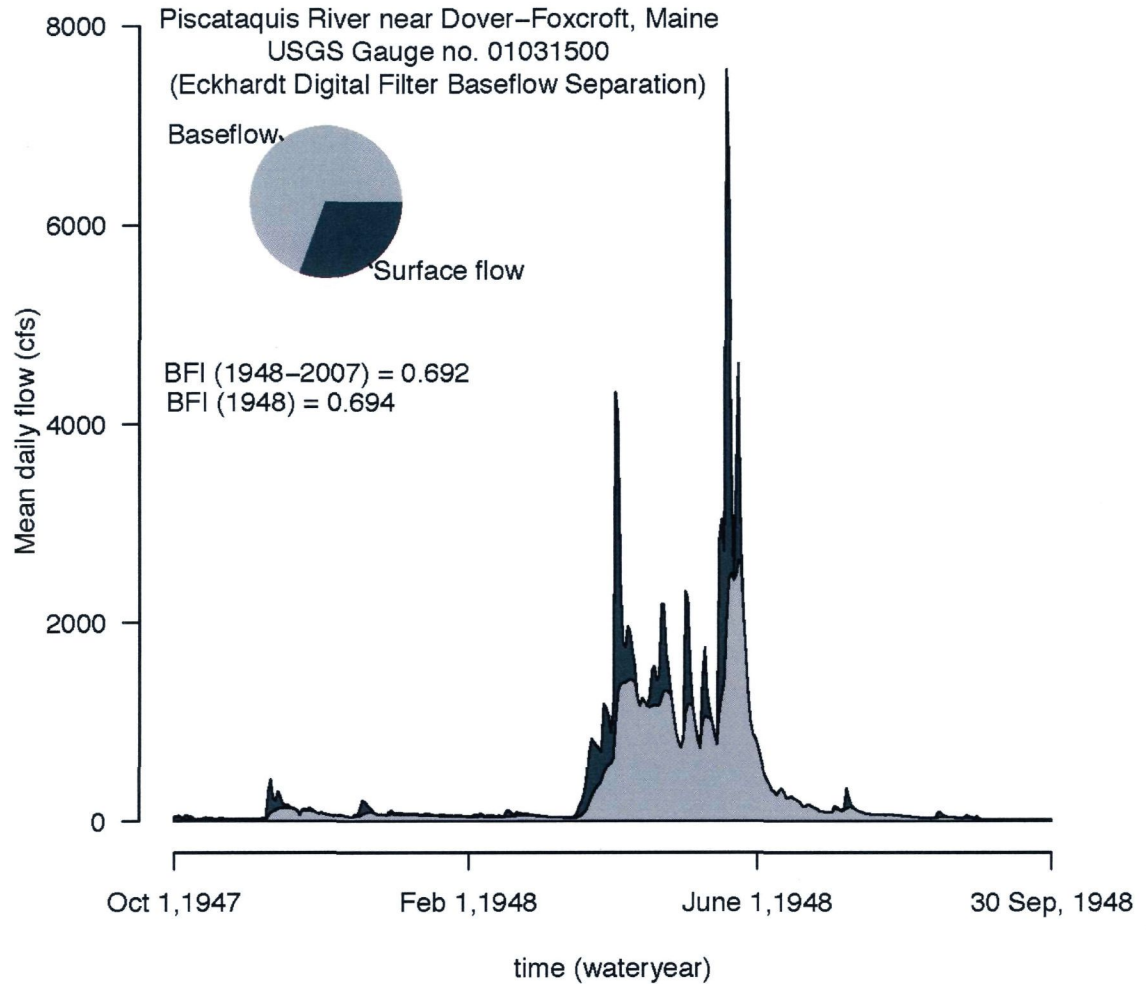
Figure 3.4. Example of Eckhardt baseflow calculation. Observed streamflow and calculated baseflow using the Eckhardt (Two parameter recursive digital filter) method for the same station and year. Contributions of surface runoff and baseflow to the total streamflow also are shown by the pie-diagram.

3.2.2. Clustering Approaches

Since there is no widely accepted clustering method available for stream regionalization, it is important to use more than one method for comparing the results, to capture the variability and increase the robustness for the study. Ward's minimum

variance algorithm from agglomerative hierarchical clustering and the K-means

algorithm from partitional clustering (ex: K-means) methods were used in this study.

Brief descriptions of the both algorithms are presented below.

3.2.2.1. K-means Clustering

The K-means clustering algorithms is developed by MacQueen (1967) and also

by Hartigan and Wong (1975.) This is a nonhierarchical method to classify or to group a

number of objects based on attributes/features into a pre-specified number of groups (K).

The grouping is done by the continuous process of calculating the sum of squares of

distances between data point and the corresponding centroids of each cluster. The

computation procedure requires a decision on the number of clustering groups (K) at the

beginning. Once the number of groups (K) has been decided, the first K number of

sample points are assigned to each cluster and these points represent initial group

centroids of single-element clusters. Then each sample is assigned to its closest centriod.

The ordinate of the centroids are recalculated once all the sample points are assigned.

Then the distance of each sample from the centroid of each of the clusters is computed

again. If a sample is found not assigned to its cluster with the closest centroid, this sample

is switched to that cluster. This reassignment of samples changes the centroids of clusters

and requires recalculation of centroids. This process is done again and again until a

sustainable convergence is achieved, that is, until an iteration that requires no new

assignments. Though K-means is a very popular and widely used clustering approach, it

is one of the least accurate methods, having many limitations. The main problem of K-

means clustering is initial grouping biases the clusters significantly especially, if the

dataset is small. If the number of data is small, different data order may produce different

clusters. It is unable to unique number of clusters. The number of clusters, K must be

specified before handing the data. Different clustering results may be produced from

different initial conditions. Data point that is very far from the centroid may pull the

centroid away from the real one. If the number of data is large, then K-means clustering

comes up with reliable result. To overcome many of it's the weaknesses it is better to use

median instead of mean.

Despite all of its weaknesses, K-means clustering is very popular among

researchers and policy-makers due to computational simplicity. Although it can be

proved that the procedure will always terminate, the k-means algorithm does not

necessarily find the most optimal configuration in a single run. To reach the most optimal

clustering, k-means algorithm is run multiple times to reduce this effect and its sensitivity

to the initial selection of centers of clusters as well.

3.2.2.2. Hierarchical Clustering

Hierarchical clustering is another major clustering technique very often used by

the hydrologists. This clustering approach produces nested sequence of clusters with the

root cluster at the top and singleton clusters at the bottom like a tree. This orientation of

clusters is also known as dendrogram. The advantage of hierarchical cluster over

partitional clustering procedures (K-means) is that it is not influenced by initialization or

local minima. Hierarchical clustering can be divided into two classes, namely:

agglomerative and divisive. Agglomerative clustering starts with configuration of little

clusters where each feature in a dataset forms it's own cluster and in every step

amalgamate smaller clusters into successively larger ones. Divisive algorithms starts with the whole feature set and continue to divide it into successively smaller clusters based on dissimilarity or distances. Several algorithms are available for agglomerative clustering; such as, single linkage, complete linkage, weighted average linkage, Ward's minimum variance. Almost all the hierarchical clustering approaches consider distance between the feature elements to establish the clusters. In single linkage clustering approach, the smallest distance between all possible pairs of feature classes of two non-singleton is taken into account. On the other hand, in complete linkage algorithm, the largest distance between all possible pair of feature classes of two non-singleton is considered. In both cases, at each step, two clusters, that are closest, are merged. If the total number of features is N, then all features will be merged in (N-1) steps. Ward's minimum variance algorithm aims to minimize the sum of square of residuals of feature vectors from the centroid of the their respective clusters and finds compact and spherical cluster. This algorithm calculates the sum of square errors of all possible pairs and then the pair with minimum sum of square errors is merged. The sum of square of errors of a single cluster can be calculated,

$$ESS_{(onegroup)} = \sum_{i=1}^{n} X_i^2 - \frac{1}{n} \left(\sum_{i=1}^{n} X_i \right)^2 \tag{3.4}$$

X is an observation of data point. In this way, sum of square of errors of all clusters can be calculated and added by the following equation,

$$ESS_{total} = ESS_{cluster1} + ESS_{cluster2} + ESS_{cluster3} + ... + ESS_{clusterj} \tag{3.5}$$

Here j = total number of clusters and ESS$_{total}$ is the "objective function". Due to its tendency of forming spherical clusters, Ward's algorithm is very useful in regionalization based on homogeneous characteristics.

3.2.3. Mann-Kendall Trend Test

Temporal trends in the daily discharge value data were evaluated using the Mann–Kendall test (Mann, 1945 and Kendall, 1975). The Mann-Kendall trend test is a widely used approach mainly because it is a non-parametric method and no assumption of normality is required (Helsel and Hirsch, 1992). Most streamflow data and their components are not distributed normally due to the problem of left censoring (no values recorded below the detection limit) and the occasional very high measurements of above the detection limit. Typically, the Mann-Kendall test results in 'no trend', or 'increasing' or 'decreasing' designations for the dataset over time. The computation of Mann-Kendall trend for forty data points or more is slightly different from that for less than forty data points. In the present study, to evaluate the overall trends in streamflow in the chosen streams for six different seasons (fall, early winter, winter, spring, early summer, summer), sixty years of streamflow data from 1948 to 2007 were considered. To find the daily trend we applied the Mann-Kendall to daily streamflow data. A particular day of a year has sixty data points for sixty consecutive years. For seasonal trend analysis, the median value for each season of a particular year is taken. Due to having datasets consist of sixty data points for both of the cases (seasonal and daily), We only describe Mann-Kendall test when there are more than 40 data points.

To find out the daily trend streamflow data, all data points of that day of all the given years are ordered sequentially, each data value is compared to all subsequent values and a new matrix is constructed to put the results. The process of comparison starts with the earliest data and it needs to be carried out for all subsequent data. If a data point is larger than it's following data point, then +1, if it is smaller then its following data point then -1 and if it is equal to the following then 0 is entered into the matrix. This process continues for all the subsequent data points and an appropriate value (1 or -1 or 0) is entered to the matrix. The summation is each row of the matrix is calculated and these row summations are added to generate the Mann-Kendall statistics (S).

Then variance of S is calculated using the following formula:

$$VAR(S) = \frac{1}{18}[n\,(n-1)\,(2n+5) - \sum_{p=1}^{q} t_p\,(t_p-1)\,(2t_p+5)] \tag{3.6}$$

Where q is the number of tied group (tied group can be defined as sample dataset having the same values) and t_p is the number of data in the pth group.

Then S and VAR(S) are used to compute test statistics, Z.

$$Z = \frac{S-1}{[VAR(S)]^{1/2}} \quad \text{if } S > 0$$

$$= 0 \qquad\qquad \text{if } S = 0$$

$$= \frac{S+1}{[VAR(S)]^{1/2}} \quad \text{if } S < 0 \tag{3.7}$$

The null hypothesis (H_0) states that the dataset shows no distinct trend and the alternative hypothesis (H_A) is that there is a trend in the dataset. The probability (*p*) of accepting H_0 is determined from the Mann-Kendall table of probabilities, based on the number of samples and absolute value of Z. In order to develop a finer resolution of

outcomes, the concept of 'level of significance' has been developed. If Z is negative and p is less than the "level of significance", then the trend is considered as "decreasing' and If Z is positive and p is less than the "level of significance", then the trend is considered as "increasing".

3.3. Results and Discussions

Long term Baseflow Index (BFI) calculated from different methods are compared and contrasted in the first section; stream regionalization and seasonal trend as well as high-resolution (daily scale) trends in streamflow along with its two components are discussed in next section.

3.3.1. Long Term BFI

After separating the baseflow from the total streamflow using all three methods (UKIH, BFLOW and Eckhardt), BFI was calculated for selected streamflow gauges (figure 3.5) for the entire time period (1948-2007). The values of BFI measured by the UKIH methods varies from 0.42 to 0.77, while in thirteen stations the value is lower than 0.5. Lower BFI indicates less stable watersheds with flashy hydrograph. Such watersheds may quickly respond to high intensity rainfalls and may cause floods during spring and fall season; on the other hand, during low flow seasons such as summer, flow may decrease substantially. The BFLOW shows higher values in all the gauges that range from 0.68 to 0.88. The Eckhardt method also measures moderate to high BFI values ranging from 0.66 to 0.77. The UKIH and the BFLOW method show strong correlation (0.967). Our results show that contrasting the Eckhardt, the UKIH and the BFLOW

methods result wide range of Baseflow Index. Correlation values of the UKIH and the

BFLOW methods with Eckhardt are 0.799 and 0.838, respectively. Though the BFI

values vary from one method to another, relative values do not change significantly. This

is a key characteristic of all these methods, which can be utilized in decision-making and

water management.

- ◆ UKIH method
- ● Eckhardt digital filter baseflow seperation method
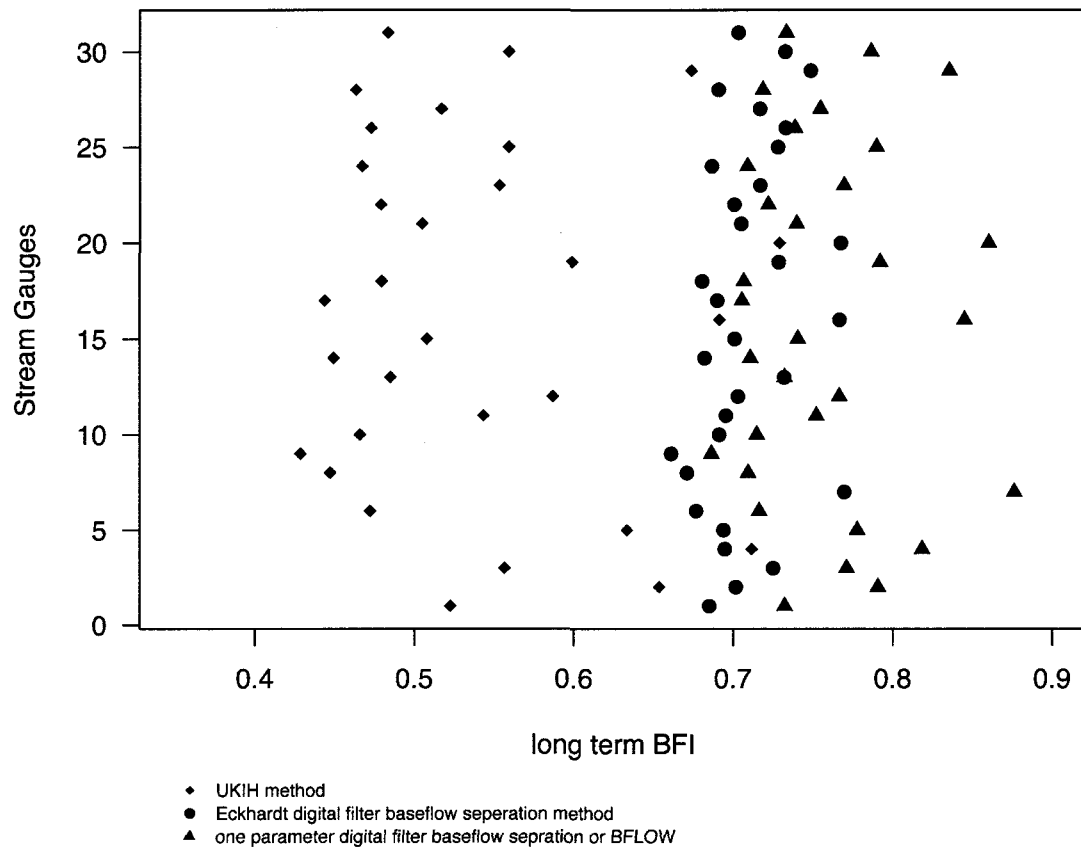- ▲ one parameter digital filter baseflow sepration or BFLOW

Figure 3.5. Long-term BFI. Comparison of long-term (1948-2007) BFI values computed in three different methods: UKIH, BFLOW and Eckhardt.

3.3.2. Stream Regionalization

Clustering is a statistical procedure by which a set of observations, data items or features are divided into subsets or groups in such a way that within a same clusters the observations are as similar as possible and in different clusters the observations are as dissimilar as possible (Rao et al. 2006). Clustering is a useful way to analyze patterns, and for classification or grouping purposes (Jain et al, 1999). Realizing its importance, researchers from various fields; such as, biology, ecology, hydrology and social sciences use it frequently (Rao et al. 2006). In hydrology, clustering methodology was mostly adopted in last two decades and widely used to analyze rainfall, floods, droughts and other basin variables (Kahya at al. 2007). In various disciplines clustering approaches follow different nomenclature and in hydrology, it is referred to as regionalization of watersheds or streams. Solin and Polacik (1994) defines a homogeneous hydrological region as an open system consisting of neighboring spatial units or basins that shows a high degree of similarity of hydrological responses. Design and construction of water management structures; for instance, roadway culverts, small bridges, dams stormwater drainage system requires estimates of flood quantiles corresponding to fifty-to-hundred years and some large structures are designed based on 100-200 year recurrence interval (Rao et al 2006, chow et al., 1988). Irrigation, hydropower, flood control measures, and soil conservation issues illustrate the importance of frequency and intensity of extreme events (Riggs, 1985). However, such analysis becomes impossible for a target watershed/site because of the paucity of historical streamflow data for long time periods. This may hinder accurate conclusions or may lead to erroneous results in estimation of flood or drought magnitude at a required recurrence period. To overcome this problem,

hydrologists often classify the watersheds in groups based on the homogeneity of available information. Then hydrological response attributes (such as: flood and low flow frequencies, flood peaks) of the target site can be calculated by using the historical streamflow at nearby watersheds/sites that are within the same group. Traditional policy-making approaches in water sensitive sectors rely on geographical, political, administrative or physiographical boundaries. However, regionalization of watersheds based on political, administrative or other boundaries do not guarantee homogeneous hydrological responses; therefore, it has limited potential in watershed and aquatic ecosystem management.

3.3.2.1. Data Manipulation

In regionalization approach, it is always challenging to select variables or attributes and a clustering procedure because of unavailability of any rigorous mathematical solutions (Bobe´e and Rasmussen, 1995). There is no single procedure developed to yield universally accepted outcomes (Kahya et al. 2007). The commonly used attributes in hydrological regionalization are summarized in table 3.2.

Table 3.2. General attributes/factors used in regionalization of streams

Factor name	Factor components
Physiographic	Drainage area, average basin slope, main stream slope, stream length, soil properties, presence of lakes, wetlands and other storages
Geographic	Latitude, longitude and altitude of watershed centroid
Geological features	Fractions of various types of bedrocks
Land use	Basin covered by forest, urban, suburban, or agricultural development
Response time	A measure of basin response time such as: basin lag, time takes to reach the peak
Meteorological	Precipitation intensities, evapotranspiration rates, average annual rainfall, high, low and average temperature
Flood	Flood frequency, time duration
Surface-base-contribution	Baseflow Index (BFI) in different season

In this study, we use seasonal BFI values for each stream-gauge as attributes for clustering. During early winter, winter and spring most of the precipitation is trapped as snow and ice and this mechanism has substantial impact on surface-base contribution in total streamflow. Since baseflow algorithms are not capable of capturing the variability due the freezing soil and river and snow melting, we are only using early summer, summer and fall BFI values. Baseflow is an important consideration during low flow seasons because streams continue to flow during extended dry periods because of contributions from groundwater/ baseflow. Watersheds, receiving high surface runoff contribution, immediately respond to high intensity rainfalls and can cause floods during spring and fall. Thus, watersheds with low BFI can be vulnerable to both drought and floods in low and high flow seasons, respectively. An increasing trend in both floods and droughts (Harry at al. 1999) again emphasized the importance of this baseflow. Considering the role of baseflow during both high-flow and low-flow seasons, we have decided to use seasonal BFI as clustering attributes. Since the study watersheds are very

diverse in basin area, they widely vary in streamflow generation. The data preparation procedures for a single stream gauge can be described in following steps:

1. Once the baseflow and surface runoff are separated from daily streamflow, a matrix is prepared with three columns. Three columns represent streamflow, baseflow and surface runoff values, respectively.

2. An array (365x60x3) is created with the rows indicate the daily values of a particular year, column indicates years and third dimension of the dataset represents streamflow, baseflow and surface runoff.

3. Subsequently in a separate array (6x60x3), seasonal streamflow, baseflow and surface flow values for each year can be calculated.

4. Seasonal BFI value for each year can be achieved by using equation 3.1.

BFI values for all six seasons (winter, spring, early summer, summer, fall and early winter) are calculated for sixty years data period from year 1947 to 2006. Limitation in baseflow algorithms in accounting for snow accumulations on the ground during early winter, winter and spring restricts us to use BFI values for these three seasons. The optimal way to capture the year-to year variability in seasonal BFI and also to decrease the dimension of the data in a reasonable way is to use the quantile values of it. So, at each gauge, three quantiles (75th or upper quantile, 50th or median and 25th or lower quantile) for early summer, summer and fall BFI values were used as clustering input data. A matrix of (31x10) was constructed where the rows represent individual gauge information, first column represents the Gauge numbers and other nine columns represent three percentile values of BFI for each of the three seasons.

3.3.2.2. Stream Clusters

For performing agglomerative hierarchical clustering, we used the R computing environment (http://cran.r-project.org/). Since only thirty-one stream gauges are used in this study, sample size within each cluster will be relatively small, if we use more than 6 clusters. It is worth noting that, a similarity/height can also be taken into consideration while choosing the number of clusters. Generally, the objective function (Eq. 3.5) decreases as the number of clusters increases. The objective function reaches to its maximum value when all the feature classes are assigned to a single cluster. The same trend was also found in this study. When all the feature streams are lumped under a single cluster, then "objective function" was 0.27. The objective function decreased as the number of clusters increased, reaching a value of 0.09 when K equaled 6. The dendrogram of stream gauges (figure 3.6) regionalization, when mapped (figure 3.7), provide a better representation of the clustering results.
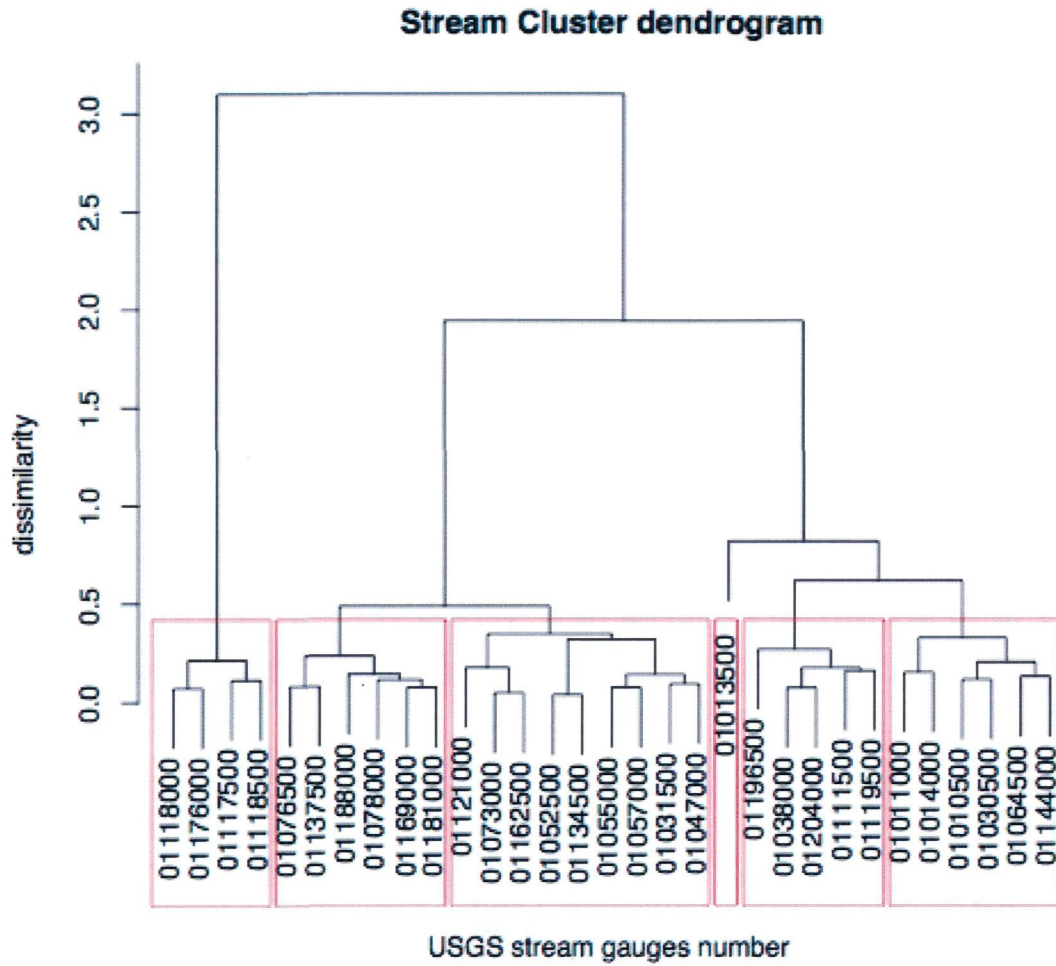
Figure 3.6. Stream gauge dendrogram using Ward's algorithm

Map of stream gauge clustering: Hierarchical clustering
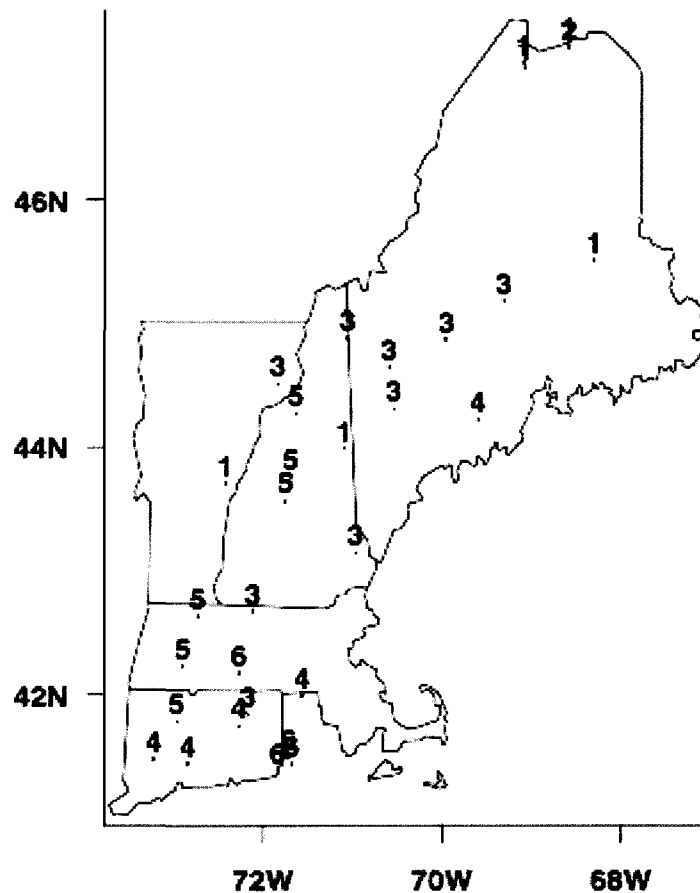
Figure 3.7. Regionalization by using hierarchical clustering. Regionalization of thirty-one New England streams into four groups using hierarchical method (Ward's algorithm) clustering approach based on UKIH-based BFI quantiles as primary precursor

To maintain the consistency with hierarchical clustering results, we selected 6 as number

of clusters. After dividing the stream gauges into six clusters by K-means clustering

approach, the obtained objective function is 0.10 that is slightly higher than the value

obtained from hierarchical Wards algorithm (0.09). Thus, Ward's algorithm minimizes

the objective function and results in more compact clusters. Cluster map obtained by K-means is represented by figure 3.8.

Map of stream gauge clustering: K-means clustering
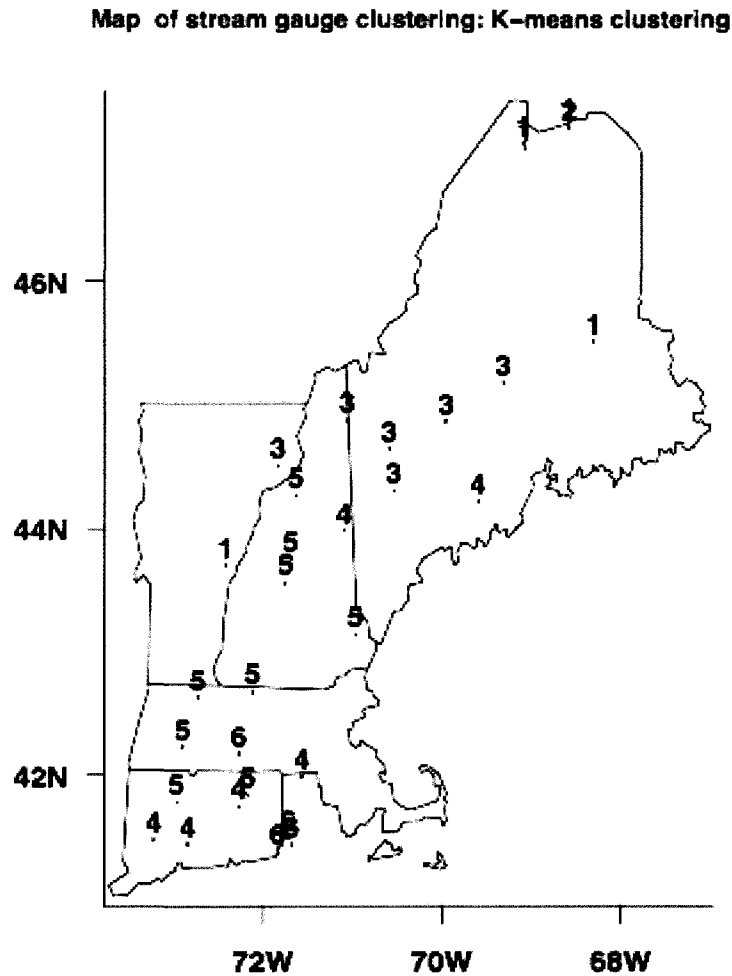
Figure 3.8. Regionalization by using K-means clustering. Regionalization of thirty-one New England streams into four groups using K-means clustering approach based on of UKIH-based BFI quantiles.

The clusters obtained from both methods are very similar. Numbers of stream gauges in obtained clusters from K-means clustering are 6, 1, 9, 5, 6, and 4 and from hierarchical clustering are 5, 1, 6, 6, 8 and 4. Only four stream gauges falls into different clusters while two different clustering approaches are used. Oyster River near Durham

(USGS no. 01073000), Priest Brook near Winchenden (USGS gauge no. 01162500) and Mount Hope River near Warrenville (USGS gauge no. 01121000) are in Cluster 3 according to hierarchical clustering; however, these gauges are in Cluster 5 based on K-means clustering. Hierarchical clustering places Saco River near Conway (USGS gauge no. 01064500) in Cluster 1, while this gauge is in Cluster 4 according to K-means approach.

While a goal of this study is out to identify homogeneous hydrologic regions, some level of heterogeneity would inevitable remain all cluster regions estimated by the two cluster analysis methods. For instance, Willimantic River near Coventry (USGS gauge no. 01119500) and Mount Hope River near Warrenville (USGS gauge no. 01121000) are very close to each other; but they fall into two different groups in both clustering analysis. Lower BFI quantile values are found during all three seasons in Mount Hope River. Although its reason is not understood with the limited available information, substantial higher watershed area of Willimantic River (121 square miles) than Mount Hope River (28.6 square miles) may be a potential reason for that. Both clustering approaches divide the neighboring four stream gauges in Northern Maine into two groups; separating Fish river (USGS gauge no 01013500) from the other streams. High variability of quantile values was found in this gauge. While its fall season quantiles are higher than that of most other gauges, its early summer quanitles are unusually low. Hosking and Wallis (1997) suggested some useful adjustment to improve the regionalization resulted from clustering algorithms: such as, (1) removing one or few more gauges from the entire data set, (2) moving ore or few gauges from one region to another, (3) subdividing a large region into smaller regions, (4) merging two or more

regions into one, (5) break up region by reassigning the gauges to other regions, (6) assigning one gauge to two or more shared regions, and (7) obtaining more data and redefining the cluster regions. For example, more stream gauges can be agglomerated in a single region. If more stream gauges are found in Group 1, Fish River near Fort Kent can be eliminated from the dataset to assign it as a homogeneous region.

3.3.3. Daily-to-Seasonal Trend in Streamflow, Baseflow, and Surface Runoff
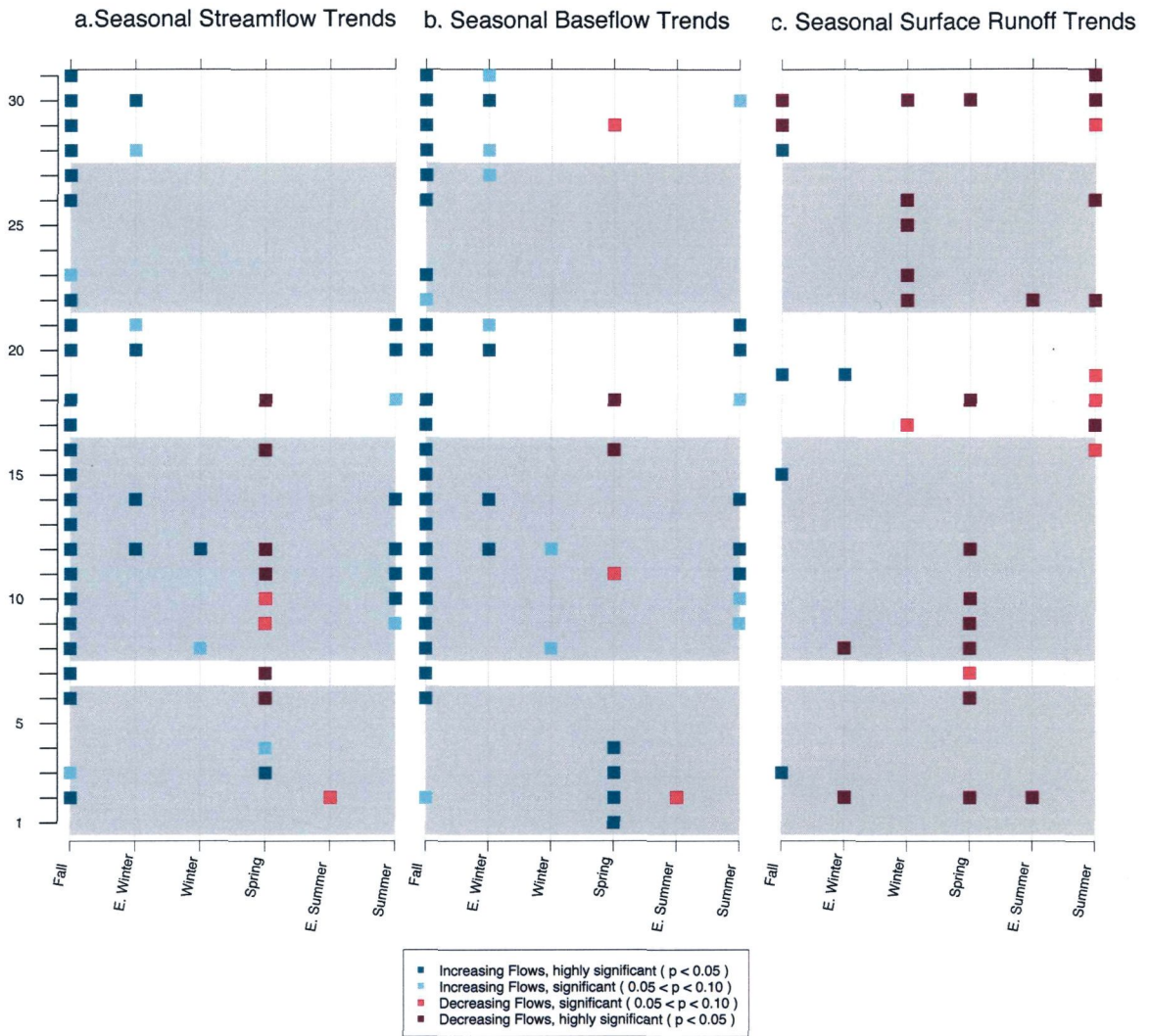
Figure 3.9. Seasonal trends in streamflow and its components calculated by Eckhardt method. (a), (b) and (c) shows the highly significant decreasing trend (S < 0.0 and p ≤ 0.05; dark orange points), significant decreasing trend (S < 0.0 and p ≤ 0.1; orange points), highly significant increasing trend (S > 0.0 and p ≤ 0.05; deep blue points), significant decreasing trend (S > 0.0 and p ≤ 0.1, sky blue points) and insignificant increasing or decreasing (p > 0.1) or no trends (S=0; no color) in streamflow, baseflow and surface flow of six seasons (winter: January 1 to March 15, spring: March 16 to May 15, early summer: May 16 to June 30, summer: July 1 to September 15, fall: September 16 to November 15, early winter: November 16 to December 31) respectively. Alternate grey and white colors are applied to differentiate between two groups where group 1 starts at the bottom and successively goes on the top as Group 2, 3, 4, 5 and 6.

Since hierarchical clustering results minimized objective function and produce more compact clusters, only resultant clusters obtained by hierarchical clustering are used for trend analysis and further discussion. Applying the Mann-Kendall trend test on total seasonal streamflow data along with surface runoff and baseflow components, we examined upward, downward and no trends at different significance level. However, seasonal trends of baseflow and surface runoff were only examined on the resultant baseflow time series data obtained by Eckhardt hydrograph analysis (figure 3.9). Seasonal trend analysis shows that the observed trend in baseflow is reflected in total streamflow for most of the seasons in most of the gauges. Since most of the New England streams are highly baseflow dominated, it is expected to find similar trend in baseflow and streamflow. Among all stream-gauging stations, 70.9% reveal highly significant and 6.4% shows significant ascending trends in baseflow contribution in the fall season. The increasing trend is also reflected in total streamflow. In early winter, six gauges from group 3, 4 and 6 (two gauges from each group) are showing upward trend in total streamflow and the same trends are found in baseflow for those gauges. Six gauges (four from Group 5, one from each of Group 4 and Group 6) shows decreasing trend in surface runoff during early winter; however, this trend is not reflected in total streamflow. In spring, two gauges from Group 1, four gauges from Group 3 and one gauge from each of Group 4 and Group 6 are showing highly significant ($p \leq 0.05$) downward trend and only gauge from Group 2 is showing highly significant ($0.05 \leq p \leq 0.10$) in surface runoff and for most of theses gauges same trend of also reflected in total streamflow. Despite the fact that seasonal trend analysis supports the validity of the stationarity concept, in other

words, doesn't show any trend for many seasons in selected New England streams, the

daily trend analysis reveals more complete story.
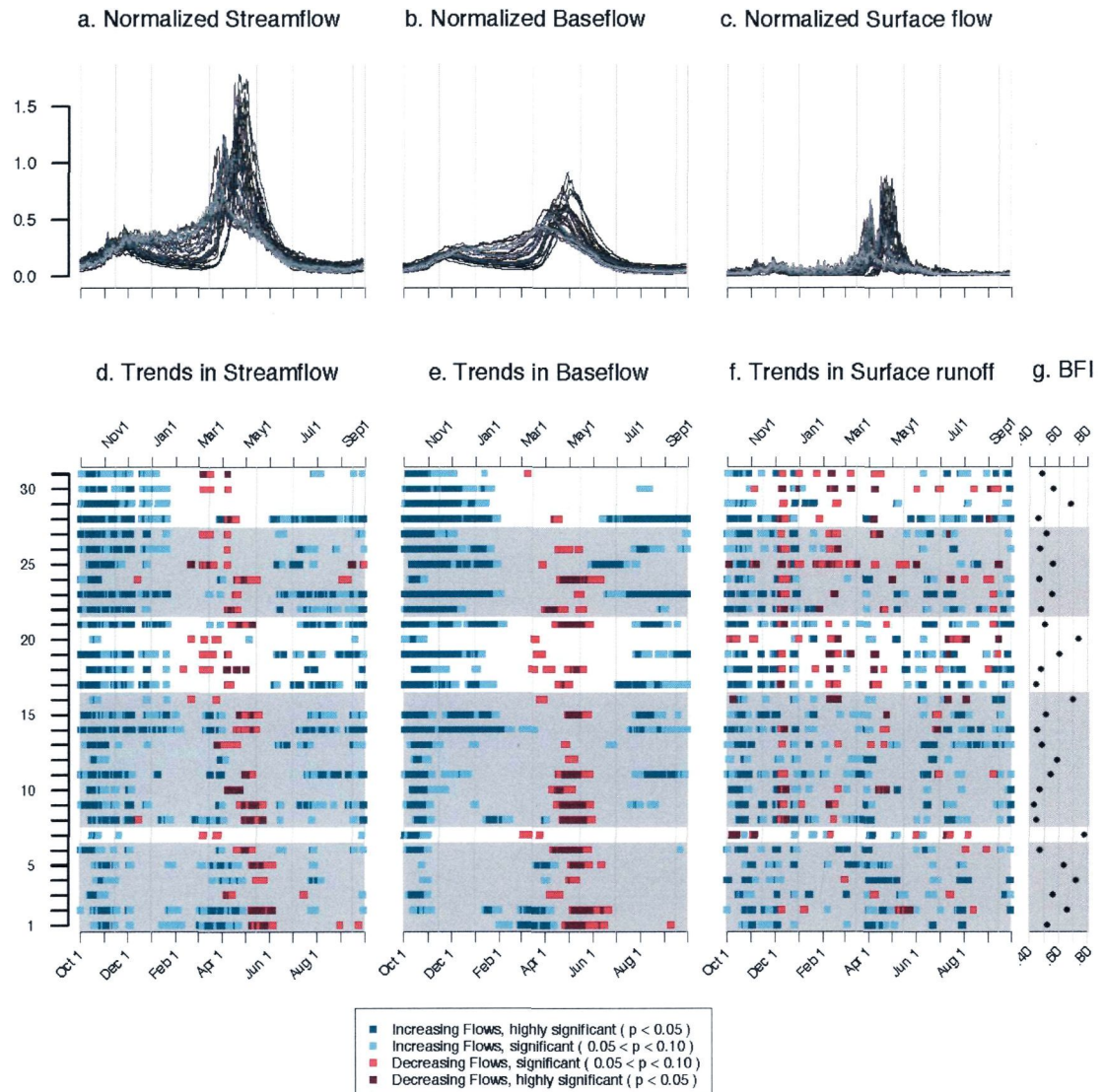
Figure 3.10. Daily trend in streamflow and its components calculated by UKIH method. In all six sub-figures horizontal axis shows the 365 days of the year starting from 1st October and vertical axis shows the number of streamflow gauges. Six Different clustering groups are distinguished by altering white and grey color. Groups are organized sequentially from bottom to top. Here (a), (b) and (c) shows the normalized daily streamflow, baseflow and surface runoff respectively achieved by UKIH method. While (d), (e) and (f) implies the highly significant decreasing trend ($S < 0.0$ and $p \leq 0.05$; dark orange points), significant decreasing trend ($S < 0.0$ and $p \leq 0.1$; orange points), highly significant increasing trend ($S > 0.0$ and $p \leq 0.05$; deep blue points), significant decreasing trend ($S > 0.0$ and $p \leq 0.1$, sky blue points) and insignificant increasing or decreasing ($p > 0.1$) or no trends ($S=0$; no color) in daily streamflow, baseflow and surface runoff respectively. The grey vertical lines differentiate sis seasons.

Applying the Mann-Kendall trend test on daily streamflow data along with their surface runoff and baseflow components, a decreasing trend in total streamflow was found in almost all gauges in late winter-to-early summer. Five Gauges in Group 1 are showing downward trend during the month of June and an increasing trend in streamflow was found before these gauges started showing decreasing trend. Figure 3.10, 3.11 and 3.12 shows trends in surface run off and baseflow calculated by UKIH, Eckhardt, and BFLOW method respectively. One stream gauge in Group 1 shows this earlier, from the beginning-to-mid April. The only gauge in Group 2 (Fish River near Fort Kent) shows descending trend during March in streamflow. Stream gauge in Group 3 show the downward trend in different time periods of spring season. No significant trend in streamflow was detected during the month of February in most of the stream gauges in Group 5 and 6. Four out of five gauges in Group 4 indicates comparatively long-term descending streamflow trend usually starts at beginning on March and ends at mid-May. In the beginning of June and July, mostly gauges from Group 3, 4, 5 and 6 start showing upward trend with little inconsistency and from the month of October almost all the gauges show a similar trend. This increasing trend continues through out the fall season, extends up to early winter and in some persisting until mid-winter. Baseflow obtained by Eckhardt (Figure 3.11) and BFLOW (Figure 3.12) algorithms are showing very similar trends to the streamflow. The trends shown in baseflow by Eckhardt and BFLOW method are replicated in streamflow for most of the gauges. Increasing trend in the baseflow was found in late fall and early winter and decreasing trend was found in mostly the month of April and May in the gauges of Group 1. Prior to the seasonal window associated with decreasing trend, an increasing trend was also found for months of March to May in four

gauges varying from gauge to gauge. Baseflow calculated by UKIH (figure 3.10) method shows downward trend only in nine stream gauges during March to May time period. Other stream gauges do not show any trend with p-value ≤ 0.10. The increasing trend during the early October to late January for most of the stream gauges is very similar to the trend in streamflow, only some cases highly significant upward trends are observed. Gauges that show upward trends during sometime in June to September also show increasing trend in baseflow during that time period. Mostly trends in baseflow are similar for all three methods with few exceptions.
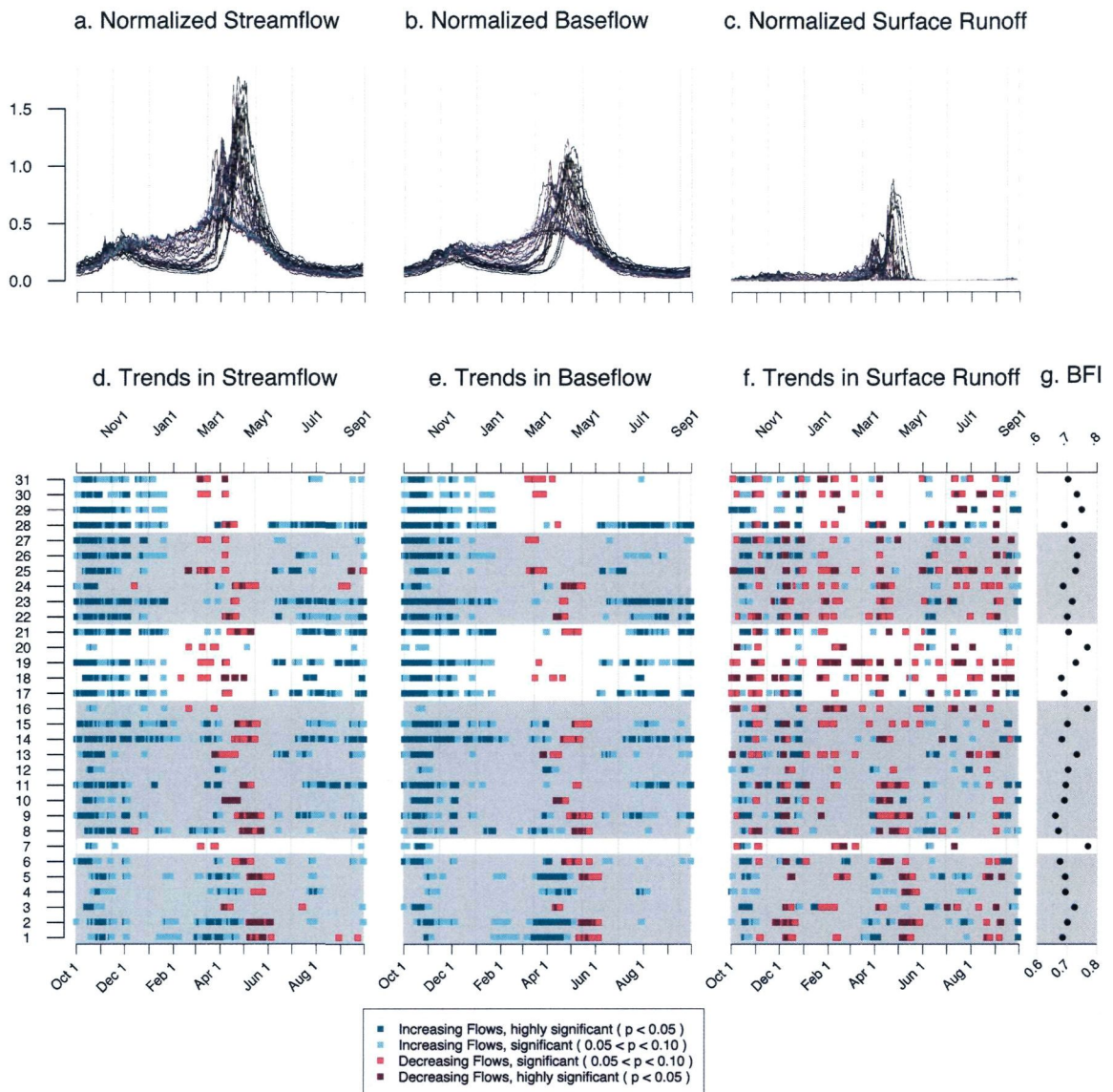
Figure 3.11. Daily trends in streamflow and its components calculated by Eckhardt method. All the descriptions are similar as figure 7, except the baseflow and surface runoff values used in this calculation are computed by Eckhardt method.
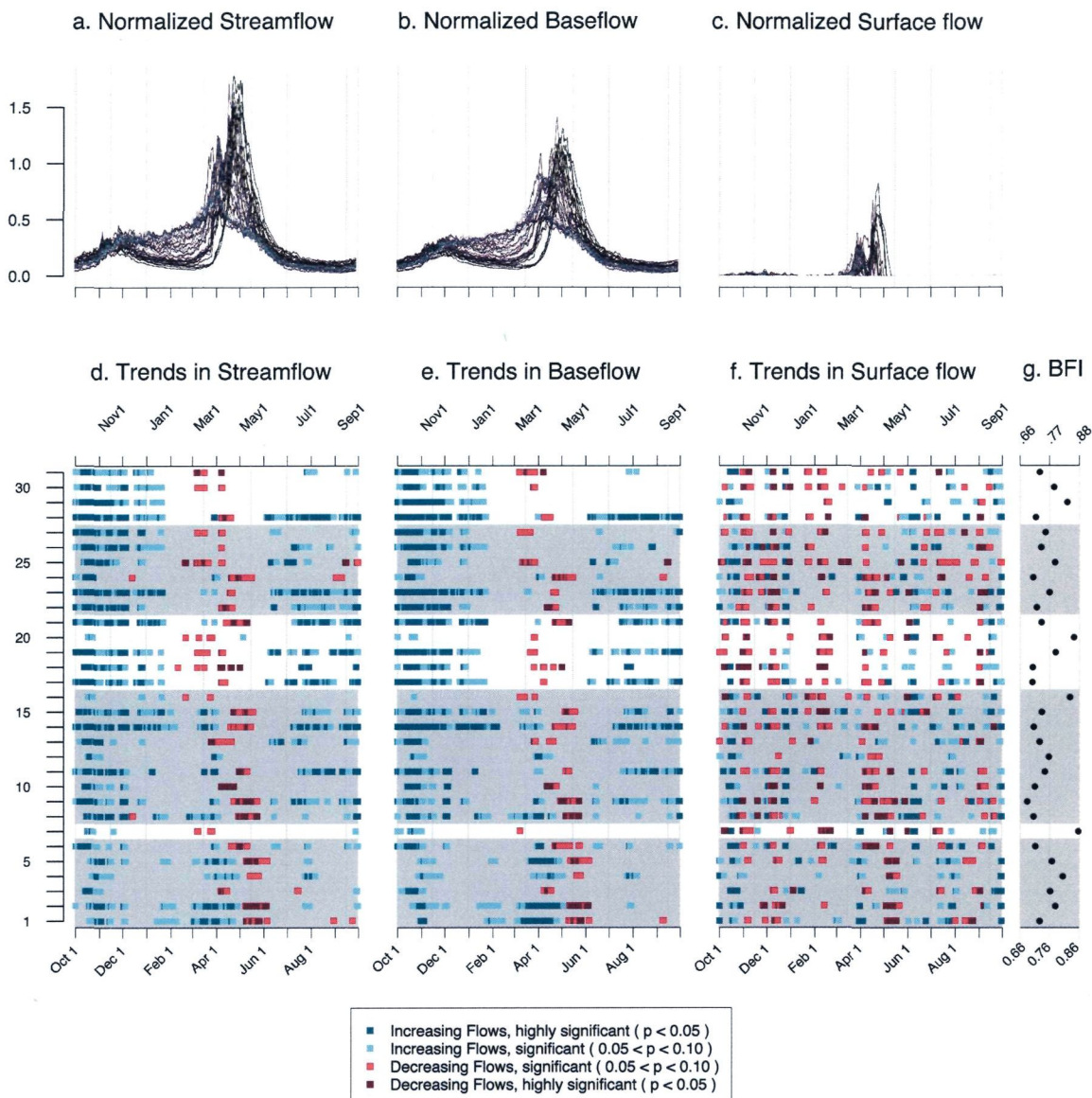
Figure 3.12. Daily trends in streamflow and its components calculated by BFLOW method. All the descriptions are similar as figure 7, except the baseflow and surface runoff values used in this calculation are computed by BFLOW method.

Trends in surface runoff are noisy and only in few times of the year patterns found throughout all the gauges or a particular group. There are also some contrasts found in trends in surface runoff calculated by UKIH and recursive digital filter methods. Increasing trend in surface runoff, calculated by UKIH method, was observed in almost all the stream gauges for the month of October and a few gauges also in November and

later. Such trends in surface runoff are only found for short time in streams of Group 1, 3 and 5 calculated by Eckhardt and BFLOW methods. Decreasing trend was found in surface runoff thought almost all the stream gauges during mid-October to mid-November, mid-November to mid-January, February and April. During the month of April or around that time most of the gauges shows decreasing trend in both baseflow and surface runoff and this trend is also reflected in total streamflow. Most other time of the year the trends are scattered and no particular patterns are found. Decreasing trend in Surface runoff calculated by UKIH is mostly group dependent. For stream gauges in Group 1, such trend is observed during June to early-September. For only the steam gauge in Group 2, it was found in early October, March and July and August. For Group 3, downward trend is scattered and five gauges shows decreasing trend in mid-December and early-to-late spring. Stream gauges in Group 4 show decreasing trend from winter to the end of spring. Stream gauges from Group 5 and 6 shows decreasing trend in mid-December. Five gauges from these two Groups show decreasing trend for long duration, usually from early January to beginning of March. Some scattered downward trends are also found in surface runoff calculated by UKIH method in some gauges of Group 5 and 6 during July, August and September.

The difference between the empirical method (UKIH) and the digital filter methods (BFLOW and Eckhardt) is that filter methods present a higher fraction of baseflow and lower fraction of surface runoff; thus a trend in baseflow plays the governing role in trend determination of total discharge most of the time. But the UKIH method allocates a higher proportion of baseflow contribution in low flow phases and a higher proportion of surface runoff in high flow periods. So, trends in low flow phase are

governed by baseflow, in high flow periods are governed by surface flow, and in moderate flow phases, trend results are a combined effect of the both surface and baseflow.

Although the specific causes of these temporal trends are not straightforward, their regionally consistent behavior is indicative of some systematic causes. Early snow melting and increasing precipitation in late winter and early spring are primarily responsible for observed trends in winter, spring and early summer. Snow carries over a substantial portion of the winter precipitation, releasing it more gradually in late spring and early summer, providing an important contribution to spring and summer soil moisture and groundwater recharge. An earlier snowmelt can lead to higher amounts of baseflow generation and aggravate winter-early spring flooding and summer droughts. Even though increasing trend in baseflow implies higher likelihood of deriving water from stored sources and a more stable watershed, it may cause as yet poorly understood changes in the ecosystem.

Here, (a), (b), and (c), of figures 3.10, 3.11 and 3.12 are normalized streamflow, baseflow and surface runoff respectively. Average daily streamflow, baseflow and surface runoff were computed for year 1948 to 2007. Then these values were normalized by median sreamflow for that time period. Normalized baseflow, and surface runoff hydrographs, respectively, show their relative contribution in different seasons of the year. A significant increasing trend in either of these two components, baseflow or surface runoff, during the high flow seasons may be an indication of increase of seasonal streamflow in the future. In the same way, as baseflow contributes most of the streamflow during low flow periods, a decreasing trend of baseflow at that time can be

alarm for future seasonal droughts. Thus the daily trend analysis approach combined with normalized flow values can be a skillful apparatus to predict shifting seasonality and change in the relative contribution of baseflow and surface runoff in the total flow.

3.4. Conclusion

Calculating baseflow from daily streamflow data by various approaches offers us a robust scrutiny of baseflow estimation. UKIH method measures the daily values by linear interpolation of the turning points and they are connected with straight lines. On the other hand, recursive digital filter methods (Both BFLOW and Eckhardt method) construct a very smooth baseflow separation. BFI values obtained from digital filter methods (BFLOW and Eckhardt) are relatively close; in contrast, UKIH method computes smaller values of BFI in all the gauges. Since there is no exact method to calculate baseflow, it is difficult to say which method provides the better estimates. Even though two watersheds with equal area receive the same amount of precipitation, the amount of streamflow generated in its streams can be very different and the relative contribution from the surface runoff and baseflow may also differ. Geological and physical features of the area, land use, and aquifer conditions and other factors are associated with this situation. Until an improved method is invented and applied to quantify the baseflow, these empirical and filter methods are helpful only as approximations. Using geochemical tracer measurement can be a further step of this investigation.

The new approach of trend analysis discussed here estimates both increasing and decreasing trends at any significance level of daily-to-seasonal streamflow and its

components for each gauge. Previous approaches have had a limited ability to quantify trends resolved to daily time scales. If two different time periods of a season with equal time span show opposite trends with nearly the same significance level, the gross result may come up with no significant trend for that season. This current framework shows the daily trend of streamflow along with its components. It helps researchers to understand which component of the streamflow is tending to fluctuate upward or downward during different time periods and their compounding impact on the trend of the total flow to the streams. Simultaneously, normalized streamflow, baseflow, and surface runoff hydrographs, respectively, show their relative contribution. A significant change in trend of either of these two components, baseflow or surface runoff, during the high flow seasons may be an indication of higher floods in the future. In the same way, as baseflow contributes most of the streamflow during low flow periods, a decreasing trend of baseflow at that time can a warning for future seasonal droughts. Thus, the daily trend analysis approach combined with normalized flow values can be a skillful apparatus to predict the shifting of seasonality and change in the relative contribution of baseflow and surface runoff in the total flow.

In summary, this study provided a clustering-based classification of stream gauges in New England. Our approach uses seasonal surface runoff and baseflow contributions. This work is a potential tool to support the water managers in decision-making in different water sensitive sectors (agriculture, industries, fisheries, ecosystem services, policy implementation, and community water supply. An improved understanding of sensitivity and severity of changes in surface runoff and baseflow is certainly important to human and ecosystem use of streamflow. Future changes, if

examined in this framework, are likely to allow a reassessment of policy, an important challenge in changing climate. It is worthy to mention that, no single approach has been demonstrated to yield universally accepted results. So, several clustering approaches can be applied for maximizing the robustness of this process. The present study has been limited to only two approaches, K-means clustering and hierarchical approach based on Ward's algorithm. Other clustering approaches can also be applied to capture the variability and increase the robustness of the study.

4. CONCLUSION

This research is designed as a place-based, use-inspired to address water resources problems in a changing hydroclimatology condition in New England. Maine's "in-stream flows and lake and ponds water levels" rule have already treated as an important initiative to maintain the required flow levels that are necessary to protect the ecosystem services. The water level requirements mentioned in this chapter need not to be maintained during a natural drought condition and such variation may last for the duration of the drought. The definition of "natural drought" in this rule is primary motivating factor of this study. A long-term paleoclimatic reconstructed PDSI provides robust estimates of the natural range of drought variability and a quantitative basis for examining the use of drought definition within the state water allocation policy. A detailed characterization of the incidence and frequency of multiyear droughts requires a long record--our analysis provides these results with a goal to inform the water policy. A brief description of some salient issues related to reliability and uncertainty of reconstructed hydroclimatic data is also presented. Consideration of multiyear droughts is an important consideration for adaptive management and policy implementation that seeks to include new scientific knowledge for policy purposes. The water policy has the potential to serve as a model for water allocation policy formulation across the nation. This analysis reinforces the view that within a changing climate, the role of scientific information is necessary for a continued assessment and updating of management and policy targets.

Yearly total streamflow shows moderate-to-strong correlation with statewide PDSI for 1951-2003 periods. Conditional probability density function between the

statewide PDSI and yearly streamflows in different gauges are developed. A watershed-specific risk for low flows was characterized by using these relationships. Our research suggests that the risk of having a low flow conditioned to a statewide PDSI is not uniform throughout the state that Hydroclimatic relationships, as well as the variable range of impacts across the state highlights the need for coordinated assessments and scientist-stakeholder interactions for improved understanding and effective implementation of Chapter 587.

Baseflow calculation by using various empirical methods offers a robust scrutiny, compare and contrast between results of different hydrograph analysis methods. While recursive digital filter methods separates very smooth baseflow separation line, UKIH method connects the turning through straight lines. Resultant BFI values calculated by UKIH method are lower than 0.50 in thirteen stream gauges. Lower BFI values imply high surface flow during spring and fall season and increase the vulnerability of floods. Groundwater recharge during that period will also be low. Low groundwater recharge during this spring can cause extended low flow periods during summer months, since during summer most of the streams are feed by the groundwater contribution and maintain the water levels.

Regionalization of streams or watersheds is important mostly for two reasons: (1) characterization hydrological responses of an ungauged stream based on homogeneity of physiographical, topological properties of a gauged stream, (2) Designing or implication of water policy over a large region which contains streams with nearly homogeneous hydrological responses. Since here is no universally accepted clustering method, two clustering approaches, such as K-means clustering and Hierarchical method (Ward's

algorithm) were applied in this study. In both cases, six clusters were created and the members fall in the same cluster in almost all cases with little discrepancies. Based on the value of objective function, the clusters obtained from hierarchical clustering are used for further study. Several clustering approaches can be applied for maximizing the robustness of this process, if the regionalization has severe importance to a particular user group.

Median flows (total streamflow, baseflow, and surface runoff) in different seasons were calculated for sixty years period. Based on this values seasonal trends were calculated by using Mann-Kendall trend test. However, this approach has a limited ability to quantify trends in particular time period o a season. Here a key consideration is that small change in median or mean may imply a large amount of changes in hydroclimatic extremes. Little change in timing a snowmelt or precipitation or temperature change can be critical in agricultural or water supply systems. If two different time periods of a season with equal time span show opposite trends with nearly for nearly same amount of days, then the gross result may not show "any significant trend" for that season. To overcome this problem, a new statistical framework is developed to compute daily trend. This current framework shows the daily trend of streamflow along with its two components, such as baseflow and surface runoff. So, it helps researchers, farmers, irrigators and policy-makers to understand which component of the streamflow is tending to fluctuate upward or downward in different time periods of the year and their compounding impact on the trend of the total flow to the stream. Simultaneously, normalized streamflow, baseflow, and surface runoff hydrographs, respectively, show their relative contribution. A significant change in trend of either of these two components, baseflow or surface runoff, during the high flow seasons may be an

indication of higher floods in the future. In the same way, as baseflow contributes most of the streamflow during low flow periods, a decreasing trend of baseflow at that time can be alarm for future seasonal droughts. Thus, the daily trend analysis approach combined with normalized flow values can be a skillful apparatus to predict the shifting of seasonality and change in the relative contribution of baseflow and surface runoff in the total flow.

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APPENDIX A

CHAPTER 587 IN-STREAM FLOWS AND LAKE AND POND WATER LEVELS

SUMMARY: This Chapter establishes river and stream flows and lake and pond water levels to protect natural aquatic life and other designated uses in Maine's waters. Instream flow requirements for Class AA, A, B, and C waters are based on natural flows that occur in Maine waters, and the uses and characteristics assigned by the water quality classification program (38 M.R.S.A. Sections 464, 465) with attention given to protecting the outstanding natural resources associated with Class AA waters. Flow is managed to provide natural variation of flow described by seasonal aquatic base flows, or other seasonally variable flows, shown to protect aquatic life resources and water quality standards. Water level requirements for Class GPA waters take into account natural variation of water levels that occur in Maine lakes and ponds, and the uses and characteristics assigned by the water quality classification program (38 M.R.S.A. Sections 464, 465-A). Water level is managed to provide variation that takes into account expected seasonal levels shown to protect aquatic resources and other water quality standards of Class GPA and downstream waters. Instream flows and water levels may be established by 3 methods: (1) standard allowable alteration, (2) by a site-specific flow designation developed through an Alternative Water Flow or Alternative Water Level, or (3) as part of a new or existing regulatory permit. A water use which fails to comply with the requirements of these rules is subject to penalties pursuant to Title 38, Section 349.

1. Applicability. The requirements established herein apply to withdrawals or other direct or indirect removal, diversion, activities, or use of these waters that causes the natural flow or water level to be altered for all non-tidal fresh surface waters of the State. Notwithstanding this, the flows and water levels established in this chapter do not apply to the following circumstances.

    A. Public emergency. Alteration of flow or water level for the purpose of protecting public health, safety, and welfare due to a sudden catastrophic event, such as for fire control. This includes water withdrawals for emergency preparedness.

    B. Storage ponds. Ponds constructed outside of a natural stream channel for the purpose of storing
water for later use, such as irrigation or snowmaking, or other man-made ponds not classified GPA under 38 M.R.S.A. Section 465-A.

    C. Nonconsumptive use. Nonconsumptive use of water is defined in 38 M.R.S.A. Section 470-A.
Notwithstanding this, an existing (as of the effective date of this chapter) point of return flow to contiguous water greater than ¼ mile from the point of withdrawal and that otherwise meets the definition of nonconsumptive use in 38 M.R.S.A. Section 470-A, is also deemed to be a nonconsumptive use. For the purposes of this chapter, non-

consumptive use is determined to have no measurable effect on flows or water levels. Flows in the segment between a point of withdrawal and a downstream point of return must be sufficient to maintain all other water quality standards, including all designated uses and characteristics of the assigned classification.

Activities that constitute a nonconsumptive use may occur during all flow and water level conditions.

D. Existing Community Water Systems operating with a Community Water System Withdrawal Certificate. Except as provided herein, Community Water Systems must comply with the applicable flow and water level requirements established in sections 4, 5, 6, 7 or 8 of this chapter. Notwithstanding this, and for the purpose of any enforcement action under this chapter, these requirements will not apply to an existing Community Water System operating within its system design capacity providing that (1) the Community Water System, so operating, cannot attain the applicable requirements, and (2) the Community Water System has received, and is operating in accordance with, or is otherwise satisfying the requirements of, a Community Water System Withdrawal Certificate issued by the Department. A Community Water System Withdrawal Certificate will be issued by the Department to any existing Community Water System that demonstrates that it cannot operate at its system design capacity and attain the applicable flow or water level requirements of this chapter. Existing Community Water Systems are those systems that are operating and withdrawing water for customer use as of the effective date of this rule. A certificate shall allow withdrawals for Community Water Systems up to their system design capacity. A certificate may include appropriate conditions that take into account the economic and technical feasibility of maintaining, and restoring to the extent feasible, all water quality standards affected by the Community Water System, including all designated uses and characteristics of the assigned classification. Economic and technical feasibility shall consider the provisions of their Legislative charter or other authority, watershed protection benefits of the existing source, and the financial viability of the Community Water System provided that the conditions and limitations of the certificate can be accomplished within the existing Public Utilities Commission approved rate schedule(s) of the system or do not in and of themselves cause a Community Water System to request a rate increase to their customers. In implementing the conditions of a certificate, the Community Water System may choose to incorporate the cost of compliance into their long-range capital plan. Any conditions included in a Community Water System Withdrawal Certificate must be reviewed and approved by the Drinking Water Program at the Department of Health and Human Services with technical assistance from the Office of the Public Advocate on economic issues, before being issued by the Department of Environmental Protection, to assure they are economically affordable and technically feasible, and will not jeopardize the safety, dependability, or the financial viability of the Community Water System. All water quality standards, as well as flows and water levels established pursuant to this chapter, remain applicable to the waters affected by the Community Water System, and will be used to assess water quality in those waters for all other purposes. The intent of the certificate process shall be to accommodate needs of Community Water Systems while striving to move towards achievement of water quality standards.

The Department may issue an amended Community Water System Withdrawal Certificate for an existing Community Water System planning a new or modified source that increases its system design capacity. Any amended certificate shall contain conditions ensuring that all water quality standards affected by the Community Water System, including designated uses and characteristics of the assigned classification, shall be maintained, or improved to the extent economically affordable and technically feasible if they were not previously in attainment. Any conditions included in an amended Community Water System Withdrawal Certificate must be reviewed and approved by the Drinking Water Program at the Department of Health and Human Services with technical assistance from the Office of the Public Advocate on economic issues, before being issued by the Department of Environmental Protection to assure they are economically affordable and technically feasible, and will not jeopardize the safety, dependability, or the financial viability of the Community Water System.

2. Definitions

    A. Natural drought condition. "Natural drought condition" means moisture conditions as measured by the Palmer Drought Severity Index with values of negative 2.0 or less.

    B. Natural variation of flow. "Natural variation of flow" in rivers and streams is the expected dynamic fluctuation in flow that naturally occurs daily, seasonally and inter-annually that provides for physical characteristics of depth, volume, and velocity necessary to (1) provide habitat conditions for all life stages of indigenous aquatic organisms, (2) provide water exchange and aeration including the interstitial water, substrate scouring and sorting, temperature moderation, wetland replenishment, sediment erosion and deposition, and channel formation, and (3) maintain biological processes of ingress and egress to habitats, migration, drift, insect emergence, organic matter and nutrient cycling, and wetlands maintenance. In establishing site-specific water flows as set forth in sections 7 and 8 of this chapter, flow variation of a magnitude, rate of change, seasonal timing, and annual occurrence, including provision for infrequent passage or release of flood flows, must be sufficient to adequately provide for the conditions and processes identified above.

    C. Natural variation of water level. "Natural variation of water level" in lakes and ponds is the expected dynamic fluctuation in water level that occurs seasonally and inter-annually that provides for physical characteristics of depth and volume necessary to (1) provide habitat conditions for all life stages of indigenous aquatic organisms, (2) provide water levels sufficient to support important physical processes including thermal stratification, temperature moderation, wetland replenishment, sediment erosion and deposition, (3) maintain biological processes of ingress and egress to habitats, maintenance of primary production, migration and movement of organisms, organic matter and nutrient cycling, and wetlands maintenance. In establishing site- specific water levels as set forth in sections 7 and 8 of this chapter, variation of a magnitude, rate

of change, seasonal timing, and annual occurrence, including provision for infrequent flood levels, must be sufficient to adequately provide for the conditions and processes identified above.

D. Normal high water. "Normal high water " means that elevation determined from a line along the shore of a Class GPA waterbody which is apparent from visible markings, changes in the character of soils due to prolonged action of the water, or from changes in vegetation and which distinguishes between predominantly aquatic and predominantly terrestrial habitat.

E. Seasonal aquatic base flow. "Seasonal aquatic base flow" is a median flow value for the following seasons: winter (January 1 to March 15), spring (March 16 to May 15), early summer (May 16 to June 30), summer (July 1 to September 15), fall (September 16 to November 15), and early winter (November 16 to December 31). Seasonal aquatic base flows are established as follows.

(1) For the winter season January 1 to March 15: a flow equal to the February median monthly flow as determined according to section 3 of this chapter.

(2) For the spring season March 16 to May 15: a flow equal to the April median monthly flow as determined according to section 3 of this chapter.

(3) For the early summer season May 16 to June 30: a flow equal to the June median monthly flow as determined according to section 3 of this chapter.

(4) For the summer season July 1 to September 15: a flow equal to the August median monthly flow as determined according to section 3 of this chapter.

5) For the fall season September 16 to November 15: a flow equal to the October median monthly flow as determined according to section 3 of this chapter.

(6) For the early winter season November 16 to December 31: a flow equal to the December median monthly flow as determined according to section 3 of this chapter.

F. System Design Capacity. "System design capacity" for authorized Community Water Systems withdrawing from surface waters shall be determined by the Department of Health and Human Services as the amount of water that is available for Community Water System purposes expressed as annual withdrawal in total gallons per year taking into consideration actual documented annual withdrawal, and the investments in and limits of the existing system infrastructure, that provides a safe and dependable supply of water for public use. Existing system infrastructure includes water treatment and distribution facilities and other necessary structures that determine how much water can be safely and dependably supplied that is present or in the process of being acquired such as through an investment bond, contractual agreement, or purchase order as of the effective date of this chapter.

G. Water User. For the purposes of this Chapter, "water user" means a person whose withdrawal or other direct or indirect removal, diversion, activity, or use of these waters by means of a structure or facility causes the natural flow or water level to be altered in any non-tidal fresh surface waters of the State.

3. Calculation of seasonal aquatic base flow values

A. Using flow records. Seasonal aquatic base flow is determined using flow records where adequate flow records are available for a specific waterbody. "Adequate flow records" means a minimum of 10 years of U.S. Geological Survey gauging records, or other equivalent flow records of good quality from unregulated waters, except as follows or as approved by the department.

(1) Where the period of flow record is at least 1 year, the available flow records may be extended by means of flow data from a nearby watershed with similar hydrologic characteristics and a minimum of 10 years of U.S. Geological Survey gauging records or other equivalent flow records.

(2) Where flow records are unavailable, flow records may be established by using a drainage area adjustment ratio for records from other gauged sites within the same drainage with at least a ten year period of record, and where the drainage areas of the gauged and ungauged sites differ by no more that 50%.

B. Without using flow records. Estimates of seasonal aquatic base flow may be calculated using the most appropriate of the following publications, or by use of a regional flow study to establish seasonal median flows for rivers and streams within a region. An adequate regional flow study should be based on a minimum of 20 stations where at least 10 independent base flow measurements have been made for each site. Where conditions, such as watershed area, fall outside of the conditions by which these estimates were calculated, estimates of seasonal aquatic base flow are considered as interim estimates and may be refined as new site-specific data is obtained.

4. Flow requirements for Class AA waters.

A. Narrative requirement for Class AA waters. Except as provided for in this section, flows in
Class AA waters shall be maintained as they naturally occur. Withdrawal or other direct or indirect removal, diversion, activity, or use of these waters that causes the natural flow to be altered may occur as provided in paragraph 4-B below.

B. Flow established by standard allowable alteration for Class AA waters.
Flow in Class AA waters may not be less than the amounts defined in subparagraphs (1), (2) and (3) below, except when natural conditions alone cause those flows to be less, or as provided by an Alternative Water Flow or regulatory permit as established in sections 7 or 8 of this chapter.

(1) When natural flow exceeds the spring aquatic base flow, 90% of the total natural flow shall be maintained.

(2) When natural flow during the early winter season exceeds the early winter aquatic base flow, 90% of the total natural flow shall be maintained.

(3) When natural flow in any other season, except as described in (1) and (2) above exceeds 1.1 times the seasonal aquatic base flow and exceeds 1.5 times seasonal aquatic base flow if aquatic base flow was calculated from methods in paragraph 3-B, 90% of the total natural flow shall be maintained.

5. Flow requirements for Class A, B, and C waters.

    A. Narrative requirement for Class A, B, and C waters. Withdrawals or other direct or indirect removal, diversion, activity, or use of Class A, B, or C waters must maintain flows sufficient to protect all water quality standards including all designated uses and characteristics of the assigned class unless as a naturally occurring condition. When flow alteration occurs in Class A, B, or C \waters that drain to a downstream Class AA water, the Class AA flow requirement, provided in section 4 of this chapter, shall be protected. Withdrawal or other direct or indirect removal, diversion, activity, or use of these waters that causes the natural flow to be altered shall occur as provided in paragraphs 5-B or 5-C below.

    B. Flow requirements for Class A waters. Flow requirements established by the standard allowable alteration in Class A waters may not be less than the seasonal aquatic base flow as defined, except when natural conditions alone cause those flows to be less. Withdrawal or other direct or indirect removal, diversion, activity, or use of Class A waters may not occur for more than two consecutive seasons under the standard allowable alteration. The Commissioner may establish, pursuant to sections 7 or 8 of this chapter, site-specific water flows that are protective of all water quality standards, including all designated uses and characteristics of those waters.

    C. Flow requirements for Class B and C waters. Flow requirements established by the standard allowable alteration in Class B and C waters may not be less than the seasonal aquatic base flow as defined, except when natural conditions alone cause those flows to be less. The Commissioner may establish, pursuant to sections 7 or 8 of this chapter, site-specific water flows that are protective of all water quality standards, including all designated uses and characteristics of those waters.

6. Water level requirements for Class GPA waters. Except as provided for in this section, water levels of Class GPA waters shall be maintained as they naturally occur. Withdrawal or other direct or indirect removal, diversion, activity or use of these waters that causes the natural water level to be altered shall occur as provided in paragraph 6-A below.

A. Water level established by standard allowable alteration. Water levels in Class GPA waters may not be less than the levels defined in subparagraphs A(1-3) below, except when natural conditions alone cause those levels to be less, or where the Commissioner has determined, as established in sections 7 or 8 of this chapter, that site-specific water levels may be established that are protective of all water quality standards, including all designated uses and characteristics of those waters.

(1) Class GPA waters without a natural surface water outlet. Water levels must be maintained within the seasonal levels listed below, unless as a naturally occurring condition: (a) within 1.0 foot of the normal high water from April 1 to July 31; and, (b) within 2.0 feet of the normal high water from August 1 until March 31.

(2) Class GPA waters with a natural surface water outlet, including beaver dams. Water level must be maintained within the seasonal levels listed below, unless as a naturally occurring condition: (a) within 1.0 foot of normal high water from April 1 to July 31; and, (b) within 2.0 feet of normal high water from August 1 to March 31. Flow in the outlet stream must be sufficient to maintain seasonal aquatic base flow, as defined in sections 4, 5, 7, or 8 of this chapter with adjustment for evaporation loss from the Class GPA water, or the natural inflow minus evaporation, whichever is less.

(3) Class GPA waters where the water level is controlled by a dam and is not used for hydropower storage or generation. Water levels must be maintained to meet all applicable water quality standards, including all designated uses and characteristics of Class GPA waters, and flow must be provided for downstream waters that will protect all water quality standards applicable to those downstream waters. Withdrawal for agriculture, aquaculture, commercial, or industrial purposes will be limited to a volume of water that is no greater than: (a) 1.0 acre-foot of water per acre of the waterbody at normal high water from April 1 to July 31. Additional volume increments may be withdrawn whenever it can be demonstrated that water replacement has occurred; and, (b) a total of 2.0 acre-feet of water per acre of the waterbody at normal high water from August 1 to March 31. Additional volume increments may be withdrawn whenever it can be demonstrated that water replacement has occurred. In no case may withdrawal cause the water level to be less than the lowest water level that can be achieved through operation of the dam. Notwithstanding the above limitations on water withdrawal amounts from GPA waters, water withdrawal may not diminish the total volume of the waterbody by more that 25%.

If a dam is removed on a Class GPA waterbody, the standard allowable alteration of water level is that alteration provided in subparagraph 6-A(2) above.

7. Alternative Water Flows and Alternative Water Levels. Alternative flows or water levels may be established following the procedure described in paragraphs 7-A and 7-B below, that allows for withdrawal, diversion, activity, or other use based on the results of a site-specific flow or water level study that is found by the Commissioner to be protective of all water quality standards, including all designated uses and characteristics, and taking into account the need for natural variation of flow or natural variation of water

level by indigenous aquatic organisms and the processes needed to maintain those resources. The Alternative Water Flow or Alternative Water Level will be made available for a 30 day review by other state natural resource agencies and the public before being approved by the Commissioner.

A. A water user or a state natural resource agency requesting an Alternative Water Flow or Alternative Water Level pursuant this paragraph shall use a form provided by the Department and shall include the following information in their filing. The information for the filing shall be developed with the assistance of the Department.

(1) The location of the proposed withdrawal.

(2) The amount, duration and frequency of the proposed withdrawal.

(3) A description of the water use, including assessment of any best management practices or water conservation practices relevant to the type of water use.

(4) The water flows or water levels that the water user proposes to maintain at the point of withdrawal, including alternative flows or water levels and management provisions that may be implemented when natural drought conditions occur.

(5) A plan for maintaining the proposed water flows or levels, including a monitoring plan that provides information on water use and flows or levels with a monitoring schedule reasonably sufficient to monitor compliance with the proposed flows or levels.

B. Upon receipt of a proposal for an Alternative Water Flow or Alternative Water Level, the
Department will schedule a field visit to assess the waterbody and the potential impacts of the proposed flows or water levels on aquatic life use and all other water quality standards relating to the waterbody, taking into account the need to protect natural variation of flow or natural variation of water level. Other interested state agencies will be provided notice of the filing and the scheduling of the field visit. At the request of an applicant, the Department may conduct field evaluations sufficient to determine an Alternative Water Flow or Alternative Water Level.

C. The Department shall maintain and make available all Alternative Water Flows or Alternative
Water Levels. An Alternative Water Flow or Alternative Water Level shall remain in effect until such time as a new Alternative Water Flow or Alternative Water Level is established by the Commissioner or a regulatory permit, as provided in Section 8, is issued.

8. Flows or water levels established by regulatory permit or water level order.

A. Flows and water levels not related to hydropower projects. Flows or water levels may be established as part of any regulatory permit or water level order issued by the Department, the Land Use Regulation Commission, or as authorized by the Cobbossee Watershed District. Flows or water levels established by regulatory permit shall be based on the results of a site-specific flow or water level study, taking into

account the need for natural variation of flow and natural variation of water level. Where an existing regulatory permit issued by the Department or the Land Use Regulation Commission establishes flows or water levels prior to the effective date of this chapter, those flows or levels shall continue for the effective period of the permit. In-stream flow and water level requirements in this chapter apply to any subsequent reissuance of a regulatory permit by the Department or the Land Use Regulation Commission. Amendments or modifications to an existing permit which do not alter the manner of use or the amount of the water withdrawal, as stated in the permit, shall not require review under this chapter. A schedule may be assigned in any reissuance of a regulatory permit that will provide a reasonable period of time for compliance with a new flow or water level requirement. In a watershed where flows or water levels have been established by a regulatory permit of the Department or the Land Use Regulation Commission, those flows or levels must be taken into account when calculating downstream flows or levels in accordance with section 7 above, during the effective term of the permit.

B. Hydropower Projects. Flows and water levels for hydropower projects, as defined in 38 M.R.S.A. § 632(3) shall be established through the Water Quality Certification process pursuant to Section 401 of the Clean Water Act, 33 U.S.C. §1341, or a permit issued pursuant to the Maine Waterway Development and Conservation Act, 38 M.R.S.A. §630 et seq., and therefore shall not be subject to or established through this Chapter, notwithstanding any other provision in this Chapter.

9. Drought flow variance for Community Water Systems. Whenever natural drought conditions, in combination with Community Water System use, cause the applicable instream flow or water level requirements of this chapter to not be maintained, the Community Water System may continue to withdraw water for public need subject to any conditions the Department may impose through the issuance of a variance pursuant to 40 CFR 131.13 (2006). Such variances may last for the duration of the drought condition and shall protect all water quality standards to the extent possible, recognizing the combined effects of a natural drought and the need to provide a safe, dependable public source of water.

10. Implementation of water flow and water level requirements.

A. Implementation of water flow and water level requirements for existing agricultural producers. An existing agricultural producer, as defined in Title 7 §353.2.A or §353.2.B, has 5 years from the effective date of this chapter to attain the applicable in-stream flow and water level requirements established in sections 4, 5, 6 or 7 of this chapter. An existing agricultural producer who has, or whose predecessor had, a permit or a written voluntary agreement establishing withdrawal limits must adhere to those limits for the 5-year period or until in compliance with the requirements established in this chapter. The Commissioner, upon recommendation of the Maine Agriculture Water Management Board, may grant an extension of the implementation period beyond the original 5 years for an agricultural producer who qualifies for the 5-year compliance period, if the Department determines that one or more of the conditions for a compliance extension established in Title 7 §353.4 apply.

B. Implementation of water flow and water level requirements for existing Community Water

Systems. An existing Community Water System has five years from the date it is notified by the Department of non-compliance with the instream flow or water level requirements of this chapter to obtain a Community Water System Withdrawal Certificate from the Department and to enter into an agreement to take all feasible actions necessary to comply with, or restore to the extent feasible, the applicable in-stream flow and water level requirements established in sections 4, 5, 6 or 7 of this chapter for the source waterbody and affected downstream waters. The Commissioner may grant an extension of this 5-year implementation period if it can be demonstrated that reasonable progress toward implementation of a Community Water System Withdrawal Certificate has occurred.

11. Watersheds most at risk from cumulative water use. Waters which do not meet one or more water quality standard due, in whole or in part, to the impact of water withdrawals are determined to be most at risk from cumulative water use. Additionally, the following waters identified in paragraphs A, B, and C below are determined to be most at risk.

       A. Class AA river or stream watersheds most at risk from cumulative water use. Watersheds which have direct withdrawal capacity that collectively amounts to 10% or more of any seasonal median flow for the season that withdrawal is intended.

       B. Class A, B, or C river or stream watersheds most at risk from cumulative water use. Watersheds which have direct withdrawal capacity that collectively amounts to 50% or more of any seasonal median flow that withdrawal is intended.

       C. Class GPA waters most at risk from cumulative water use. Waters which have direct withdrawal capacity that collectively amounts to 80% or more of the available water for any defined period as provided by the standard allowable alteration.

       D. This definition does not constitute a regulatory standard and is not intended as such. It is only intended to identify watersheds that are most at risk from cumulative water use for the purpose of directing future efforts to address water use planning.

12. New activities in state waters. Any activity altering the flow or water level of classified state waters that requires a new or reissued regulatory permit from the Department or the Land Use Regulation Commission, as of the effective date of this chapter, will be regulated according to the flow and water level requirements in this chapter. An Alternative Water Flow or Alternative Water Level may be incorporated in any new or reissued regulatory permit.

13. Certain activities prohibited in Class AA waters. Any activity in Class AA water that causes an alteration from the naturally occurring flow must protect all water quality

standards, including the free-flowing characteristic. In-stream dams or other permanent alterations of the natural stream channel are prohibited. Activities, including the construction of structures in or adjacent to a waterbody to provide water withdrawal, or temporary diversions necessary as part of approved construction activity, may be permitted according to provisions in the Natural Resources Protection Act (38 M.R.S.A. Section 480).

14. Legal Water Rights Not Affected. Determinations under this chapter do not confer legal water rights or constitute a determination of reasonableness of use with respect to other existing or future water users.

AUTHORITY: 38 M.R.S.A. § 470-H

EFFECTIVE DATE: August 24, 2007

APPENDIX B

TREE-RING DATA SITES FOR PDSI DATA RECONSTRUCTION IN MAINE

Serial no	Site name	Latitude	Longitude	Beginning year	Ending year	Species info
1	Ironbound island	44.25 N	68.09 W	1665	1982	Pcru Red Spruce
2	Wizard Pond	44.35 N	68.10 W	1692	1982	Pcru Red Spruce
3	Number Three Pond	45.19 N	68.15 W	1686	1981	Tsca Eastern Hemlock
4	Acadia National park Regional	44.22 N	68.16 W	1840	1992	Pist eastern White Pine
5	Carnolt	45.41 N	68.06 W	1880	1994	Frni Black Ash
6	Acadia National park stand 6	44.25 N	68.17 W	1840	1992	Pist eastern White Pine
7	Acadia National park stand 8	44.20 N	68.18 W	1886	1992	Pist eastern White Pine
8	Basin Pond (B)	44.28 N	70.03 W	1818	1973	Tsca Eastern Hemlock
9	Cathedral Pine	45.10 N	70.27 W	1795	1973	Pire Red Pine
10	Sugarloaf Mountain	45.02 N	70.19 W	1773	1976	Pcru Red Spruce
11	Elephant Mountain	44.46 N	70.46 W	1667	1977	Pcru Red Spruce
12	Traveler Mountain	46.04 N	68.51 W	1728	1976	Pcru Red Spruce
13	Hamlin Ridge	45.55 N	68.54 W	1610	1981	Pcru Red Spruce
14	Reed Pond	46.16 N	69.00 W	1639	1986	Tsca Eastern Hemlock
15	ST. Francis	47.20 N	68.80 W	1896	1994	Frni Black Ash
16	Gridstone	45.74 N	68.58 W	1863	1994	Frni Black Ash
17	Sag Pond	46.46 N	69.10 W	1674	1986	Thoc Northern White Cedar
18	Soper Brook, West Branch	46.00 N	69.20 W	1692	1982	Frni Black Ash
19	West Enfield	45.24 N	68.61 W	1864	1994	Frni Black Ash
20	Burnham	44.67 N	69.40 W	1873	1994	Frni Black Ash
21	Portage	46.73 N	68.47 W	1872	1994	Frni Black Ash

APPENDIX C

PALMER DROUGHT SEVERITY INDEX

Palmer Drought Severity Index (Palmer, 1965) is widely used index that provides a measurement of moisture condition of a particular month in relatively homogeneous region. This index is developed based on the water balance formula taking into account of precipitation, temperature and Available Water Content (AWC) of the soil. This method uses a model "bucket" consists of two soil layers. The top layer is assumed to contain 1 in. of moisture and is known as "surface soil layer". This layer is exposed to precipitation and evaporation. It is also assumed that evaporation occurs at its potential rate until any moisture is available in soil and no recharge occurs to the lower layer until soil of surface layer exceeds the field capacity. Further assumption is that the loss from the lower layer depends on initial moisture condition, potential evapotranspiration (PE) and Available Water Content (AWC) of the soil. Runoff occurs only when both layers reach to the field capacity.

Although they are not directly used to compute the dryness or wetness, computation of potential value of evapotranspiration, recharge, loss and runoff are still important. When evapotranspiration reaches to the maximum value that could exist is defined as potential evapotranspiration (Palmer, 1965) and it can be determined by using computed using the Thornthwaite method (Wells et al. 2004). Potential loss is an expression for maximum conditions of loss and is defined as "amount of moisture that could be lost from the soil provided the precipitation during the period were zero" (Palmer, 1965). Palmer also defines Climatically Appropriate For Existing Conditions

(CAFES) as precipitation ($\hat{p}$) needs to maintain the normal soil moisture (Wells et al. 2004) and mathematically can be expressed as,

$$\hat{P} = \alpha PE + \beta PR + \gamma PRO + \delta PL$$

Where α, β, γ and δ are coefficients for evapotranspiration, recharge, runoff and loss, respectively. PE, PR, PRO and PL are expressing potential evapotranspiration, potential recharge, potential runoff and potential loss, respectively.

Moisture Departure can be computed by subtracting the CAFES precipitation from the actual precipitation, P. Thus,

$$d = P - \hat{P}$$

The meaning of same magnitude of moisture departure, d highly differs from one place to another as well as one time period to another. So, Provide a general expression of d, palmer used a coefficient K, which is refined by another coefficient K'.

$$K' = 1.5 \log_{10}\left(\frac{\frac{\overline{PE} + \overline{R} + \overline{RO}}{\overline{P} + \overline{L}} + 2.8}{\overline{D}}\right) + 0.5$$

$$K = \frac{17.67}{\sum\limits_{i=1}^{12} \overline{D}i} K'$$

Moisture anomaly index, Z can be computed by the following information and this index is used to measure the dryness or wetness for a particular month without considering the prior information.

$$Z = dK$$

The Palmer Drought Severity Index (PDSI) for a given month by suing the following formula:

$$Xi = 0.897X_{i-1} + \left(\frac{1}{3}\right)Zi$$

This equation takes into account of previous month PDSI value. Summation of one third of current months Z-value and 0.897 times last months PDSI is the PDSI value for current month.

It is requested to cite the following references for more information regarding this subject, from which the above description is summarized:

Palmer, W.C. 1965. Meteorological drought. Research Paper No. 45, U.S. Department of Commerce Weather Bureau, Washington, D.C.

Wells, N, Goddard, S., Hayes, M. J., A Self-Calibrating Palmer Drought Severity Index, J. Climate, 17, 2335–2351 (2004).

BIOGRAPHY OF THE AUTHOR

Avirup Sen Gupta was born in Rangpur, Bangladesh on 26 December 1984. He was raised and lived in the same city until he was seventeen. There he completed his 10th grade from Rangpur Zilla School in 2000 and 12th grade from Rangpur Govt. College in 2002. He then attended the Khulna University of Engineering and Technology (KUET), and graduated in 2007 with a Bachelor's degree in Civil Engineering. Then he became involved with OrasInvest (Bangladesh) Ltd. as a BOQ/Site Engineer in telecommunication tower construction projects. As an inhabitant of Bangladesh, Avirup is well acquainted with intolerable miseries, damage and losses due to climate extremes like floods, cyclones, water contamination and droughts. To find noble solutions of such water-related problems, Avirup joined at the University of Maine in Fall 2008 as a graduate student. He is also a student member of American Society of Civil Engineers (ASCE).

After receiving his degree, Avirup will be joining at the Utah State University as a PhD student from Fall 2010. Avirup is a candidate for the Master of Science degree in Civil Engineering from The University of Maine in August 2010.