Handbook of Environmental Engineering 15

Lawrence K. Wang
Chih Ted Yang *Editors*

Modern Water Resources Engineering

Humana Press

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VOLUME 15
HANDBOOK OF ENVIRONMENTAL ENGINEERING

Modern Water Resources Engineering

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Preface

The past 35 years have seen the emergence of a growing desire worldwide that positive actions be taken to restore and protect the environment from the degrading effects of all forms of pollution—air, water, soil, thermal, radioactive, and noise. Since pollution is a direct or indirect consequence of waste, the seemingly idealistic demand for "zero discharge" can be construed as an unrealistic demand for zero waste. However, as long as waste continues to exist, we can only attempt to abate the subsequent pollution by converting it to a less noxious form. Three major questions usually arise when a particular type of pollution has been identified: (1) How serious are the environmental pollution and water resources crisis? (2) Is the technology to abate them available? and (3) Do the costs of abatement justify the degree of abatement achieved for environmental protection and water conservation? This book is one of the volumes of the *Handbook of Environmental Engineering* series. The principal intention of this series is to help readers formulate answers to the above three questions.

The traditional approach of applying tried-and-true solutions to specific environmental and water resources problems has been a major contributing factor to the success of environmental engineering, and has accounted in large measure for the establishment of a "methodology of pollution control." However, the realization of the ever-increasing complexity and interrelated nature of current environmental problems renders it imperative that intelligent planning of pollution abatement systems be undertaken. Prerequisite to such planning is an understanding of the performance, potential, and limitations of the various methods of environmental protection available for environmental scientists and engineers. In this series of handbooks, we will review at a tutorial level a broad spectrum of engineering systems (processes, operations, and methods) currently being utilized, or of potential utility, for pollution abatement. We believe that the unified interdisciplinary approach presented in these handbooks is a logical step in the evolution of environmental engineering.

Treatment of the various engineering systems presented will show how an engineering formulation of the subject flows naturally from the fundamental principles and theories of chemistry, microbiology, physics, and mathematics. This emphasis on fundamental science recognizes that engineering practice has in recent years become more firmly based on scientific principles rather than on its earlier dependency on empirical accumulation of facts. It is not intended, though, to neglect empiricism where such data lead quickly to the most economic design; certain engineering systems are not readily amenable to fundamental scientific analysis, and in these instances we have resorted to less science in favor of more art and empiricism.

Since an environmental engineer must understand science within the context of applications, we first present the development of the scientific basis of a particular subject, followed by exposition of the pertinent design concepts and operations, and detailed explanations of their applications to environmental conservation or protection. Throughout the series, methods of system analysis, practical design, and calculation are illustrated by numerical examples.

These examples clearly demonstrate how organized, analytical reasoning leads to the most direct and clear solutions. Wherever possible, pertinent cost data have been provided.

Our treatment of environmental engineering is offered in the belief that the trained engineer should more firmly understand fundamental principles, be more aware of the similarities and/or differences among many of the engineering systems, and exhibit greater flexibility and originality in the definition and innovative solution of environmental system problems. In short, an environmental engineer should by conviction and practice be more readily adaptable to change and progress.

Coverage of the unusually broad field of environmental engineering has demanded an expertise that could be provided only through multiple authorships. Each author (or group of authors) was permitted to employ, within reasonable limits, the customary personal style in organizing and presenting a particular subject area; consequently, it has been difficult to treat all subject materials in a homogeneous manner. Moreover, owing to limitations of space, some of the authors' favored topics could not be treated in great detail, and many less important topics had to be merely mentioned or commented on briefly. All authors have provided an excellent list of references at the end of each chapter for the benefit of the interested readers. As each chapter is meant to be self-contained, some mild repetition among the various texts was unavoidable. In each case, all omissions or repetitions are the responsibility of the editors and not the individual authors. With the current trend toward metrication, the question of using a consistent system of units has been a problem. Wherever possible, the authors have used the British system (fps) along with the metric equivalent (mks, cgs, or SIU) or vice versa. The editors sincerely hope that this redundancy of units' usage will prove to be useful rather than being disruptive to the readers.

The goals of the *Handbook of Environmental Engineering* series are: (1) to cover entire environmental fields, including air and noise pollution control, solid waste processing and resource recovery, physicochemical treatment processes, biological treatment processes, biotechnology, biosolids management, flotation technology, membrane technology, desalination technology, water resources, natural control processes, radioactive waste disposal, hazardous waste management, and thermal pollution control; and (2) to employ a multimedia approach to environmental conservation and protection since air, water, soil, and energy are all interrelated.

This book is Vol. 15 of the *Handbook of Environmental Engineering* series, which has been designed to serve as a water resources engineering reference book as well as a supplemental textbook. We hope and expect it will prove of equal high value to advanced undergraduate and graduate students, to designers of water resources systems, and to scientists and researchers. The editors welcome comments from readers in all of these categories. It is our hope that the book will not only provide information on water resources engineering, but will also serve as a basis for advanced study or specialized investigation of the theory and analysis of various water resources systems.

This book, *Modern Water Resources Engineering*, covers topics on principles and applications of hydrology, open channel hydraulics, river ecology, river restoration, sedimentation and sustainable use of reservoirs, sediment transport, river morphology, hydraulic engineering, GIS, remote sensing, decision-making process under uncertainty, upland erosion modeling, machine learning method, climate change and its impact on water resources, land application, crop management, watershed protection, wetland for waste disposal, water conservation, living machines, bioremediation, wastewater treatment, aquaculture system management, environmental protection models, and glossary for water resources engineers.

The editors are pleased to acknowledge the encouragement and support received from their colleagues and the publisher during the conceptual stages of this endeavor. We wish to thank the contributing authors for their time and effort, and for having patiently borne our reviews and numerous queries and comments. We are very grateful to our respective families for their patience and understanding during some rather trying times.

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Introduction to Hydrology

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CONTENTS

Abstract *Hydrology* deals with the occurrence, movement, and storage of water in the earth system. Hydrologic science comprises understanding the underlying physical and stochastic processes involved and estimating the quantity and quality of water in the various phases and stores. The study of hydrology also includes quantifying the effects of such human interventions on the natural system at watershed, river basin, regional, country, continental, and global scales. The process of water circulating from precipitation in the atmosphere falling to the ground, traveling through a river basin (or through the entire earth system), and then evaporating back to the atmosphere is known as the hydrologic cycle. This introductory chapter includes seven subjects, namely, hydroclimatology, surface water hydrology, soil hydrology, glacier hydrology, watershed and river basin modeling, risk and uncertainty analysis, and data acquisition and information systems. The emphasis is on recent developments particularly on the role that atmospheric and climatic processes play in hydrology, the

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advances in hydrologic modeling of watersheds, the experiences in applying statistical concepts and laws for dealing with risk and uncertainty and the challenges encountered in dealing with nonstationarity, and the use of newer technology (particularly spaceborne sensors) for detecting and estimating the various components of the hydrologic cycle such as precipitation, soil moisture, and evapotranspiration.

Key Words Hydrologic cycle • Hydroclimatology • Precipitation • Streamflow • Soil moisture • Glaciology • Hydrologic statistics • Watershed modeling • Hydrologic data acquisition.

1. INTRODUCTION

Hydrology deals with the occurrence, movement, and storage of water in the earth system. Water occurs in liquid, solid, and vapor phases, and it is transported through the system in various pathways through the atmosphere, the land surface, and the subsurface and is stored temporarily in storages such as the vegetation cover, soil, wetlands, lakes, flood plains, aquifers, oceans, and the atmosphere. Thus, hydrology deals with understanding the underlying physical and stochastic processes involved and estimating the quantity and quality of water in the various phases and stores. For this purpose, a number of physical and statistical laws are applied, mathematical models are developed, and various state and input and output variables are measured at various points in time and space. In addition, natural systems are increasingly being affected by human intervention such as building of dams, river diversions, groundwater pumping, deforestation, irrigation systems, hydropower development, mining operations, and urbanization. Thus, the study of hydrology also includes quantifying the effects of such human interventions on the natural system (at watershed, river basin, regional, country, continent, and global scales). Water covers about 70 % of the earth surface, but only about 2.5 % of the total water on the earth is freshwater and the rest is saltwater (NASA Earth Observatory website). Of the total amount of the earth's freshwater, about 70 % is contained in rivers, lakes, and glaciers and about 30 % in aquifers as groundwater [1].

A related term/concept commonly utilized in hydrology is *hydrologic cycle*. It conveys the idea that as water occurs in nature, say in the form of rainfall, part of it may be temporarily stored on vegetation (e.g., trees), the remaining part reaches the ground surface, and in turn part of that amount may infiltrate and percolate into the subsurface, and another part may travel over the land surface eventually reaching the streams and the ocean. In addition, part of the water temporarily stored on the vegetation canopy, the soil, depression pools, the snow pack, the lakes, and the oceans evaporates back into the atmosphere. That process of water circulating from the start of the precipitation, traveling through the river basin (or through the entire earth system), and then evaporating back to the atmosphere is known as the hydrologic cycle.

This introductory chapter includes seven subjects, namely, hydroclimatology, surface water hydrology, soil hydrology, glacier hydrology, watershed and river basin modeling, risk and uncertainty analysis, and data acquisition and information systems. The intent is to discuss some basic concepts and methods for quantifying the amount of water in the various components of the hydrologic cycle. However, the chapter content cannot be comprehensive because of space limitations. Thus, the emphasis has been on recent developments particularly on the role that atmospheric and climatic processes play in hydrology, the advances in hydrologic modeling of watersheds, the experiences in applying statistical concepts and laws for dealing with risk and uncertainty and the challenges encountered in dealing with nonstationarity, and the use of newer equipment (particularly spaceborne sensors) for detecting and estimating the various components of the hydrologic cycle such as precipitation, soil moisture, and evapotranspiration. Current references have been included as feasible for most of the subjects.

2. HYDROCLIMATOLOGY

All years are not equal when it comes to hydrology and climate. The year-to-year response of the hydrologic system that results in floods or droughts is driven by the nonlinear interactions of the atmosphere, oceans, and land surface. While a deterministic understanding of the complex interactions of these systems may be near impossible, certain patterns have been identified that have been correlated to particular hydrologic response in different locations.

These identified patterns range in spatial and temporal scales as depicted in Fig. 1.1. At the lower left are the smaller spatial scale and relatively fast evolving atmospheric phenomena that can impact midlatitude weather systems resulting in different hydrologic outcomes. As the space and time scale expand, ocean processes start to play a role, and the patterns or relations are coupled ocean–atmosphere events that can span multiple years and play a role in spatial patterns of hydrologic response as well as magnitude. The largest spatial and longest time-scale processes come from the oceanic system and can play a role in decadal variability of hydrologic response.

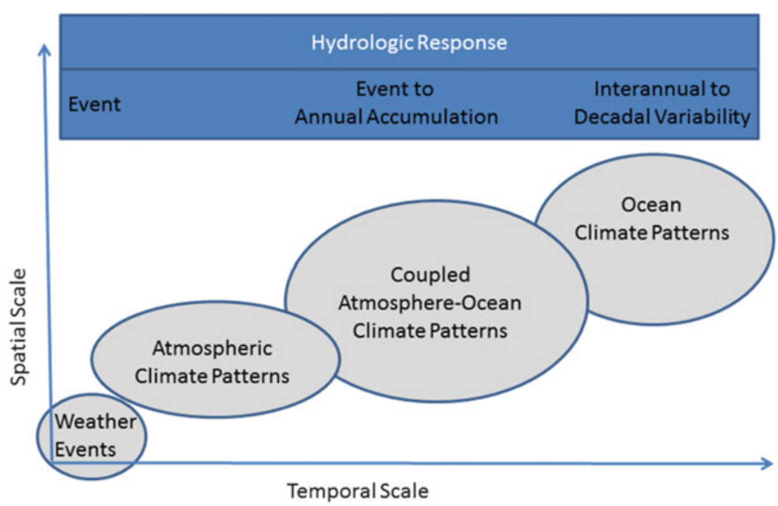

Fig. 1.1. Schematic depicting the range of spatial and temporal scale of climate patterns and associated hydrologic response.

The strength of a given pattern and the interactions among multiple identified patterns across multiple scales play an important role in the type and level of hydrologic response (e.g., flood or drought). In addition, changes to the hydroclimatic system arising from natural and anthropogenic elements can impact the hydrology in a given location. This section presents an overview of the climate system and its potential impact on hydrology. Specified patterns in the ocean and atmospheric systems will be shown and related to hydrologic response in locations where a clear connection has been identified. Hydrologic response to climate change will also be reviewed noting some of the latest work completed in this area.

2.1. The Hydroclimatic System

The climate for a given location is a function of the nonlinear interactions of multiple physical processes occurring simultaneously in the atmosphere, ocean, and land surface systems. The atmosphere responds to changes in solar radiation, tilt and rotation of the earth, atmospheric constituents, and distribution of heat input from the ocean and land surface systems. The ocean system responds to changes in wind stresses from the atmosphere as well as from thermohaline currents at various depths that may be influenced by the bathymetry of the different ocean basins and relative positions of the continents. The land system is influenced by the temperature of both atmosphere and ocean and develops its own pattern of heating that is radiated back to the atmosphere as long-wave radiation. All of these elements play a role in the evolution of weather systems that result in different hydrologic outcomes.

While physical equations have been developed to describe the different time-evolving elements of these systems, using them directly to determine their impact on hydrology is extremely complex and filled with uncertainty. An alternative approach is to look for characteristic recurring patterns in the hydroclimatic system and examine their correlation with hydrologic time series to determine if there is a potential link. In some cases, the correlation may not be strong, but this may be due to the impact of other patterns or the combination of processes. Because of this, greater insight may be gained by examining hydrologic response through the use of probability distributions conditioned upon a given hydroclimatic patterns or collection of patterns. This can be limited by the available realizations provided by the observed record.

In the following sections, three scales of hydroclimate patterns identified in Fig. 1.1 are presented along with their potential impact on hydrologic response. Examples from observations or studies that have identified regions having significant correlative response will be highlighted. Additional factors that can impact extreme events also will be pointed out. Finally, a discussion of hydrologic response due to climate change will be provided in the context of scale and forcing of the hydroclimate system.

2.2. Hydroclimatic System Patterns: Atmospheric Patterns

Atmospheric patterns are the smallest in spatial scale and shortest in temporal scale. They are considered hydroclimatic patterns as they are larger than the scale of weather systems which is often referred to as the synoptic scale [2]. The synoptic scale has a spatial extent the size of time-varying high- and low-pressure systems that form as part of the time evolution of the atmosphere. These systems are usually 500–1,000 km in spatial extent with extreme cases being larger. The life cycle of these events as they impact a given location results in a time scale on the order of 3 days. Patterns of atmospheric hydroclimate evolve on the order of weeks and have a spatial scale of several thousand kilometers. In addition, the pattern itself may result in the formation of planetary waves that can impact weather systems far removed from the pattern itself.

One of the most well-known atmospheric hydroclimate patterns is the *Madden-Julian Oscillation* [3]. This continent-sized cluster of convective activity migrates across the tropics with a periodicity ranging from 30 to 90 days. It is thought that the convective activity excites planetary scale waves that can interact with weather systems in the midlatitudes which can lead to enhanced precipitation for some locations. Maloney and Hartmann [4, 5] studied the influence of the Madden-Julian Oscillation and hurricane activity in the Gulf of Mexico.

A second pattern of atmospheric hydroclimate that can influence midlatitude weather systems and the resulting hydrologic response is the *Arctic Oscillation* [6]. This pressure pattern between the Northern Hemisphere polar region and northern midlatitudes has two phases called the positive phase and negative phase. In the positive phase, the higher pressures are in the northern midlatitudes which results in storm tracks shifting northward and confining arctic air masses to the polar region. As a result, places like Alaska, Scotland, and Scandinavia tend to be wetter and warmer, while the Mediterranean region and western United States tend to be drier. The negative phase is the opposite with more cold air movement to the northern midlatitudes and wetter conditions in the western United States and Mediterranean regions. The time frame for the oscillations is on the order of weeks. The oscillation does not directly cause storms but influences pressure tendencies in the midlatitudes that can facilitate the formation of storms in select regions. Additional information on this phenomenon can be found on the National Oceanographic and Atmospheric Administration's (NOAA) Climate Prediction Center's web pages (e.g., http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/teleconnections.shtml).

2.3. Hydroclimatic System Patterns: Coupled Atmosphere-Ocean Patterns

Coupled atmosphere-ocean patterns extend from the scale of atmospheric phenomena to the scale of select regions in ocean basins. These patterns can persist from months to years and can have significant influence on atmospheric circulation patterns that result in changes to storm tracks and observed hydrologic conditions at given locations.

The best-known phenomenon of this type is the *El Niño/Southern Oscillation* (ENSO). The ENSO pattern was discovered in pieces by different researchers in the late 1800s [7]. Subsequent studies showed that the variously observed pressure differences, changes in surface ocean currents, and changes in the equatorial sea surface temperatures in the eastern Pacific Ocean from the dateline to the coast of South America were all part of the ENSO pattern. There are three phases to ENSO: a warm (El Niño) phase, a cool (La Niña) phase, and a neutral phase. Transitions between phases occur in time periods ranging from 2 to 7 years. While this is a tropical phenomenon, hydrologic impacts occur across the globe as the global

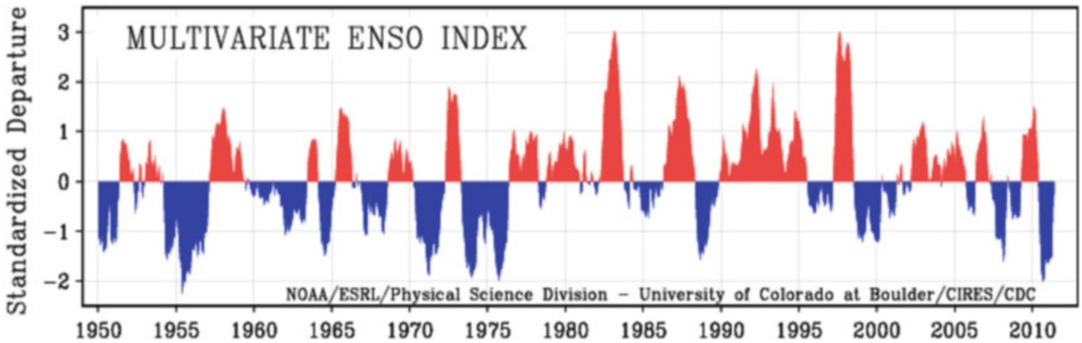

Fig. 1.2. Plot of multivariate ENSO index from 1950 to present. *Blue regions* are associated with La Niña events and *red regions* are associated with El Niño events (source: NOAA, ESRL, http://www.pmel.noaa.gov/co2/file/Multivariate+ENSO+Index) (*Color figure online*).

atmosphere responds to the tropical ocean/atmosphere conditions that can persist for more than a year. Further information on ENSO can be found in Philander [7] and NOAA's Climate Prediction Center web pages.

The United States has several regions that have seemingly well-defined hydrologic responses to the different phases of ENSO. The southeast tends to have colder drier winters during La Niña. In the west, the Pacific Northwest tends to be wetter (drier) than average during La Niña/El Niño, while the Southwest is drier (wetter) than average [8]. Cayan et al. [9] investigated the relationship of ENSO to hydrologic extremes in the western United States. Gray [10], Richards and O'Brien [11], and Bove et al. [12] have investigated links of Atlantic Basin hurricane activity to the state of ENSO which has a distinct impact on hydrologic condition in the Gulf States and Eastern seaboard.

It is important to realize that the ENSO phenomenon tends to impact the atmospheric circulation patterns. Variability in the positioning of the atmospheric circulation patterns relative to the land surface can have a significant influence on the observed hydrologic response for some locations. Figure 1.2 shows a plot of the Multivariate ENSO Index, an index based on multiple factors to determine the strength of the El Niño or La Niña event [13]. In Fig. 1.2, red regions are associated with El Niño events, and blue regions are associated with La Niña events.

2.4. Hydroclimatic System Patterns: Ocean System Patterns

The oceanic component of the hydroclimate system has the longest time scale of evolution which can lead to interannual to decadal influences on hydrologic response. Ocean system patterns that influence the hydroclimate system are often tied to sea surface temperature patterns that are driven in part by ocean circulations due to heat content and salinity variations across the depth and breadth of the ocean basins.

One pattern of oceanic hydroclimate is the *Pacific Decadal Oscillation* (PDO). This sea surface temperature pattern spans the entire Pacific Ocean north of the equator ([14]; Minobe [15]). In the Atlantic basin, the *Atlantic Multidecadal Oscillation* (AMO) has been identified by Xie and Tanimoto [16]. Figure 1.3 shows a plot of the PDO and AMO.

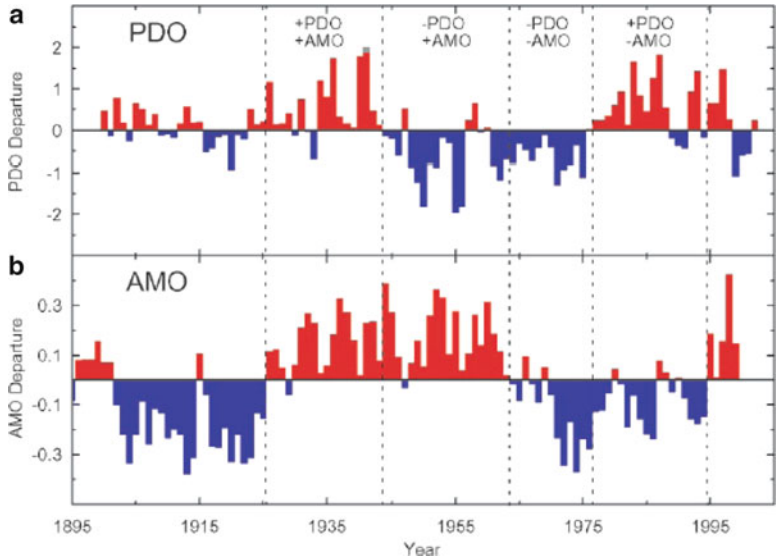

Fig. 1.3. Time series of PDO and AMO (with permission from [17]).

For the PDO, there are two phases, a warm phase and a cold phase. In the warm phase of the PDO, a pool of warmer than average sea surface temperatures extends across the northeast Pacific. It is surrounded by a ring of cooler-than-normal water to the west. The cold phase has a cooler-than-average pool of water in the northeast Pacific with a ring of warmer water surrounding it to the west. The transition between a warm and cold phase occurs between 10 and 30 years. Its discovery was an outcome of a search for causal mechanisms of changes in fisheries patterns along the coast of North America [14, 18]. Due to ocean patterns' long time period of evolution, they tend to serve as a backdrop upon which the shorter time-scale processes occur. In that sense, impacts tend to relate more to decadal variability rather than specific event influence. Correlations with hydrologic conditions can be found in numerous studies and reviews (e.g., [19–21]).

Like the PDO, the AMO has a warm and cold phase defined primarily by SST patterns. For the North Atlantic and the AMO, any linear trends are removed from the SST time series prior to determining the phase of the AMO to take anthropogenic climate change into account. Variability in the AMO is associated with the ocean's thermohaline circulation. Correlations of the AMO to Northern Hemisphere precipitation and air temperature patterns are also numerous (e.g., [22–24]).

2.5. *Interactions Across Scales and Extreme Events*

The phenomena mentioned above do not evolve in isolation, and at any given time, multiple features can be influencing midlatitude weather patterns and their associated hydrologic response. In some cases, the interactions can mitigate the influence of one pattern and may muddle the correlation with hydrologic response in a given location. On the other hand, there may be times when interactions between the processes occur in such a way that an unusually extreme event results. In these cases, there may be additional processes such as *atmospheric rivers* [25] that come into play.

Atmospheric rivers are narrow bands of high concentrations of atmospheric water vapor that extend from the tropics to the midlatitudes. When these water vapor bands interact with the right atmospheric dynamics, extreme precipitation events tend to occur. The relation of processes such as atmospheric rivers and other hydroclimate patterns and their associated impact on hydrologic response is an area of open research. NOAA's Climate Prediction Center tracks a large collection of these hydroclimate system patterns and has more information and references on their website.

2.6. Climate Change

Changes in atmospheric composition impacting the radiative balance of the atmosphere can have significant impacts on hydrologic processes. Increasing temperatures lead to higher freezing altitudes which lead to higher elevation snow lines. Higher snow lines mean greater watershed area contributing to runoff during a precipitation event which will result in more direct runoff and possible higher peak flows. Higher snow lines may result in smaller runoff volumes during the snowmelt period, changing the shape of the annual hydrograph. Higher snow lines may also change the local water balances resulting in changes to watershed yields for water supply purposes.

Methods for assessing hydrologic impacts of climate change are varied. Impacts to annual and monthly hydrology for water supply purposes have looked at scaled changes to monthly flow volumes using ratios (e.g., [26–28]). Hydrologic models have been used to determine changes to flows using temperature and precipitation change estimates from global climate model projections (e.g., [29–31]). However, these simulations assume that the model calibration for historical hydrologic conditions is also appropriate for future climate conditions. Such questions suggest that more research is needed into watershed processes and their potential change in relationship to each other with different climate conditions. Another option for expanding the hydrologic realizations of the observed record is to use paleoclimate estimates of hydrologic variables. For example, this has been done in the United States Bureau of Reclamation's Lower Colorado Study [32]. Other methodologies will likely be developed as more refined climate change projection information becomes available and more planning studies require consideration of climate change impacts.

2.7. Remarks

Climate plays a significant role in hydrologic response. Year-to-year variations in peak flows, low flows, or annual totals can be related to specific hydroclimatic patterns through a variety of correlative methods. Several hydroclimatic patterns have been identified with phases lasting from days to years to decades. Climate change may cause fundamental shifts in hydrologic processes at a given location that may impact the correlative relation between the climate phenomena and local hydrologic response. Continued research and development is needed to move beyond correlative relations to a greater understanding of the physical processes that enable climate to impact weather that impacts hydrologic response. While a deterministic mapping of these processes may not be possible due to the complexity and interaction of the different phenomena, there should be opportunity for examining conditional probability distributions and their evolution based on the evolution of the climate system.

3. SURFACE WATER HYDROLOGY

3.1. Precipitation

The lifting of moist air masses in the atmosphere leads to the cooling and condensation which results in precipitation of water vapor from the atmosphere in the form of rain, snow, hail, and sleet. Following the cooling of air masses, cloud droplets form on condensation nuclei consisting of dust particles or aerosols (typically < 1 μm diameter). When the condensed moisture droplet is larger than 0.1 mm, it falls as precipitation, and these drops grow as they collide and coalesce to form larger droplets. Raindrops falling to the ground are typically in the size range of 0.5–3 mm, while rain with droplet sizes less than 0.5 mm is called drizzle.

There are three main mechanisms that contribute to lifting of air masses. *Frontal lifting* occurs when warm air is lifted over cooler air by frontal passage resulting in *cyclonic* or *frontal* storms. The zone where the warm and cold air masses meet is called a *front*. In a *warm front*, warm air advances over a colder air mass with a relatively slow rate of ascent causing precipitation over a large area, typically 300–500 km ahead of the front. In a *cold front*, warm air is pushed upward at a relatively steep slope by the advancing cold air, leading to smaller precipitation areas in advance of the cold front. Precipitation rates are generally higher in advance of cold fronts than in advance of warm fronts. Oftentimes, warm air rises as it is forced over hills or mountains due to *orographic lifting* as it occurs in the northwestern United States, and the resulting precipitation events are called *orographic storms*. Orographic precipitation is a major factor in most mountainous areas and exhibits a high degree of spatial variability. In *convective lifting*, warm air rises by virtue of being less dense than the surrounding air, and the resulting precipitation events are called *convective storms* or, more commonly, *thunderstorms*.

Natural precipitation is hardly ever uniform in space, and spatially averaged rainfall (also called *mean areal precipitation*) is commonly utilized in hydrologic applications. Mean areal precipitation tends to be scale dependent and statistically nonhomogeneous in space. Precipitation at any location (measured or unmeasured) may be estimated using an interpolation scheme that employs linear weighting of point precipitation measurements at the individual rain gauges over a desired area as

$$\hat{P}(x) = \sum_{i=1}^{N} w_i P(x_i), \tag{1.1}$$