

# Evapotranspiration Modeling

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*"In space, no one can hear you think."*

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# 1 Evapotranspiration Modeling

## 1.1 Introduction to Evapotranspiration

Evapotranspiration represents one of the most fundamental yet complex processes in Earth's environmental systems, serving as the invisible engine that drives water movement across our planet's surface. At its core, evapotranspiration (ET) describes the combined process of water transfer from land to atmosphere, encompassing both direct evaporation from soil and water bodies, as well as transpiration from vegetation. This seemingly simple definition belies the intricate web of physical, biological, and chemical interactions that govern this phenomenon, making it both a critical component of the global water cycle and one of the most challenging processes to quantify accurately. The term itself emerged in the early 20th century as scientists recognized that separating evaporation and transpiration in natural systems was often impractical, if not impossible, given their interconnected nature and shared meteorological drivers.

To truly appreciate evapotranspiration, we must first distinguish its constituent parts while acknowledging their inseparability in most natural settings. Evaporation refers to the phase change of water from liquid to vapor directly from surfaces such as soil, water bodies, or wet vegetation. This physical process depends primarily on the availability of energy, typically from solar radiation, and the existing vapor pressure deficit between the evaporating surface and the overlying air. Transpiration, by contrast, represents the biological process by which plants draw water from soil through their root systems, transport it upward through vascular tissues, and release it as vapor through microscopic pores called stomata on leaf surfaces. This plant-mediated water loss serves crucial physiological functions beyond mere water movement—it facilitates nutrient transport, enables gas exchange for photosynthesis, and provides evaporative cooling that protects plant tissues from thermal damage. When we speak of evapotranspiration, we acknowledge these processes as they occur simultaneously in the real world, with their relative proportions varying dramatically across different ecosystems, seasons, and environmental conditions.

The significance of evapotranspiration extends far beyond its role as a mere component of the water cycle. Within the global hydrological system, ET represents the largest pathway by which water returns from land surfaces to the atmosphere, dwarfing streamflow and groundwater discharge in most regions. On an annual basis, approximately 65,000 cubic kilometers of water enter the atmosphere through evapotranspiration from land surfaces alone—a volume equivalent to more than 26 million Olympic-sized swimming pools. This tremendous flux of water vapor not only redistributes water across Earth's surface but also carries with it substantial amounts of latent heat energy, fundamentally influencing regional and global climate patterns. The condensation of this water vapor eventually drives precipitation elsewhere on the planet, creating atmospheric rivers that transport moisture across continents and sustain ecosystems far from their original source.

The components and processes that comprise evapotranspiration exhibit remarkable diversity across Earth's varied landscapes. Soil evaporation, the direct loss of water from the soil matrix to the atmosphere, follows a characteristic pattern that shifts as surface moisture declines. Following rainfall or irrigation, soil evaporation occurs at its maximum potential rate, limited only by available energy. As the soil surface dries, this

process becomes increasingly restricted by the need for water to move upward through increasingly difficult pathways within the soil matrix. Eventually, a thin dry layer forms at the surface, effectively severing the hydraulic connection between deeper soil moisture and the atmosphere, at which point evaporation drops dramatically to low levels maintained only by vapor diffusion through this barrier. The physics governing this transition were first systematically studied in the 1950s by scientists like Philip and Gardner, who developed mathematical frameworks that remain foundational to our understanding of soil water dynamics today.

Plant transpiration adds another layer of complexity to evapotranspiration, introducing biological regulation into what would otherwise be a purely physical process. The journey of water from soil through plant to atmosphere involves overcoming resistance at each step: uptake by roots, transport through the xylem, movement through leaf tissues, and finally diffusion through stomatal pores. Stomata, those remarkable structures that balance the conflicting needs for carbon dioxide intake and water conservation, can adjust their aperture in response to environmental cues including light intensity, atmospheric humidity, carbon dioxide concentration, and soil water availability. This dynamic regulation means that transpiration rates can vary by orders of magnitude over the course of a single day, even as environmental conditions remain relatively constant. The discovery of stomatal function in the late 19th century revolutionized our understanding of plant-water relations, revealing plants not as passive wicks but as active regulators of their water status.

Beyond these primary components, evapotranspiration also includes interception loss—the evaporation of water stored on vegetation surfaces during precipitation events. In dense forests, particularly those in humid regions, interception can account for 10-40% of gross precipitation, effectively short-circuiting the water cycle by returning water to the atmosphere before it reaches the forest floor. This process plays a crucial role in the microclimates of forest ecosystems, maintaining elevated humidity levels that influence everything from understory plant communities to animal behavior patterns. The quantitative importance of interception was first documented in the early 20th century through painstaking measurements in experimental forests, providing some of the earliest evidence that vegetation could significantly modify local water balances.

Groundwater evapotranspiration represents another important pathway, particularly in arid and semi-arid regions where deep-rooted plants, known as phreatophytes, can directly access water tables several meters below the surface. Species like mesquite in the American Southwest, tamarisk along western rivers, and eucalypts in Australia have evolved extensive root systems that form hydraulic bridges between groundwater reserves and the atmosphere. In some cases, this process can deplete aquifers at rates comparable to human pumping, creating conflicts between ecological water needs and water resource development. The recognition of groundwater-dependent ecosystems has become increasingly important in water management, particularly as climate change intensifies water scarcity in many regions.

The global distribution of evapotranspiration reveals fascinating patterns that reflect the interplay of climate, vegetation, and land surface characteristics. Tropical rainforests, despite receiving abundant rainfall, exhibit some of the highest annual ET rates on Earth, typically 1500-2000 millimeters per year, due to continuous energy availability and evergreen vegetation. These regions function as massive continental engines, constantly recycling moisture through the atmosphere and generating a significant portion of their own rainfall—

a process sometimes described as “flying rivers.” By contrast, deserts may receive similar or even greater amounts of solar energy but evaporate only 50-200 millimeters annually due to limited water availability. Temperate forests and grasslands typically fall between these extremes, with annual evapotranspiration rates of 400-1000 millimeters depending on precipitation patterns and seasonal temperature variations.

The connection between evapotranspiration and atmospheric moisture transport represents one of the most important yet often underappreciated aspects of Earth’s climate system. The water vapor entering the atmosphere through ET doesn’t simply disappear—it moves with winds, sometimes traveling thousands of kilometers before condensing and falling as precipitation. This atmospheric recycling means that water evaporated from agricultural fields in the American Midwest may contribute to rainfall in the Eastern United States, while moisture from the Amazon rainforest supports precipitation throughout South America. The concept of precipitation recycling, first systematically quantified in the 1990s, has revealed that in some continental interiors, more than half of annual rainfall originates from evapotranspiration within the same region, creating a delicate balance between land surface management and water availability.

Beyond its role in water cycling, evapotranspiration fundamentally regulates Earth’s energy balance through the process of latent heat exchange. When water evaporates, it absorbs approximately 2.45 megajoules of energy per kilogram—energy that is then released elsewhere when the water vapor condenses into cloud droplets or precipitation. This latent heat flux represents a massive energy transport mechanism, moving heat from regions of net evaporation (typically tropical and subtropical areas) to regions of net condensation (often higher latitudes). Without this atmospheric heat engine, Earth’s tropical regions would be substantially warmer while polar regions would be significantly colder. The recognition of evapotranspiration as a key component of Earth’s climate system has grown throughout the past century, from early energy balance studies in the 1940s to sophisticated satellite observations today.

To navigate the complex world of evapotranspiration science, researchers and practitioners rely on several key concepts and metrics that provide standardized frameworks for measurement and comparison. Perhaps the most fundamental distinction exists between potential evapotranspiration (PET) and actual evapotranspiration (AET). PET represents the maximum amount of water that could evaporate and transpire from a surface under unlimited water availability, determined solely by atmospheric conditions. AET, by contrast, reflects the actual water loss that occurs given real-world constraints of water availability, vegetation characteristics, and surface properties. This distinction, first formalized by C. Warren Thornthwaite in the 1940s, provides crucial insight into water stress conditions—when AET falls significantly below PET, it indicates that vegetation or soil moisture is limited by water availability rather than atmospheric demand.

The concept of reference evapotranspiration (ET<sub>o</sub>) emerged from practical needs in agriculture and water management to provide a standardized basis for estimating crop water requirements across different locations and seasons. ET<sub>o</sub> represents the evapotranspiration rate from a hypothetical reference surface—typically a well-watered grass cover of standardized height (0.12 meters), surface resistance (70 seconds per meter), and albedo (0.23). This artificial construct, first proposed by Howard Penman and later standardized by the Food and Agriculture Organization (FAO) in 1998, allows for the calculation of crop-specific evapotranspiration through simple multiplication by crop coefficients (K<sub>c</sub> values) that account for differences between

the reference surface and actual crops. The FAO Penman-Monteith equation for calculating ETo has become the global standard, implemented in thousands of irrigation management systems worldwide.

Crop coefficients themselves represent another crucial concept in applied evapotranspiration science, providing dimensionless values that scale reference evapotranspiration to specific crops, growth stages, and management conditions. These coefficients capture the integrated effects of crop height, roughness, leaf area, stomatal characteristics, and management practices on evapotranspiration rates. For example, a typical Kc curve for corn might begin around 0.3 during early growth stages, peak at 1.15 during mid-season when the crop is fully developed, and decline to 0.6 as the crop matures and senesces. The development of regionally calibrated crop coefficients has become a major focus of agricultural research, particularly as changing climate conditions and new crop varieties alter traditional water use patterns.

The measurement and expression of evapotranspiration rates requires attention to units and conversion factors that can sometimes create confusion across disciplines. The most common units include millimeters per day (equivalent to liters per square meter per day), which conveniently represents the depth of water that would be lost from a surface; and watts per square meter, which expresses the energy flux associated with the phase change of water. For agricultural applications, rates are sometimes expressed in cubic meters per hectare per day, while atmospheric scientists may prefer kilograms per square meter per second. These various units reflect the different perspectives from which evapotranspiration is studied—as a water balance component, an energy flux, or a management parameter. The ability to convert between these units seamlessly has become essential as interdisciplinary research on evapotranspiration has grown in importance.

As we embark on this comprehensive exploration of evapotranspiration modeling, it's worth reflecting on how our understanding of this fundamental process has evolved from simple observations to sophisticated mathematical representations. The journey from ancient farmers' empirical knowledge of crop water needs to today's satellite-based global monitoring systems spans centuries of scientific discovery, technological innovation, and practical application. Each advancement in our ability to measure, understand, and predict evapotranspiration has unlocked new possibilities for managing water resources, adapting to climate change, and understanding Earth's interconnected systems. The sections that follow will trace this remarkable evolution, examining the historical development of evapotranspiration science, the physical principles that govern these processes, the diverse methods used to measure and model them, and their applications across fields from agriculture to urban planning. In doing so, we'll discover that evapotranspiration, while invisible to the naked eye, shapes nearly every aspect of our relationship with water and energy on this planet.

## 1.2 Historical Development of Evapotranspiration Science

This remarkable evolution begins not in a laboratory, but in the fields of ancient agriculturalists who, through generations of observation, developed an intuitive understanding of crop water needs. The sophisticated irrigation systems of ancient Egypt, Mesopotamia, and the Indus Valley were not merely feats of engineering but testaments to empirical knowledge about water loss from soils and plants. These early farmers, though lacking the language of physics, recognized that thirsty crops in hot, windy conditions required more water than those in cool, calm weather. They understood, at a practical level, the fundamental relationship between

weather and plant water use that would take scientists millennia to quantify. The qanats of ancient Persia, masterful underground aqueducts that transported groundwater across arid landscapes, demonstrated an early grasp of minimizing evaporation losses, a key consideration that remains central to modern water management. This accumulated wisdom, passed down through oral tradition and practical application, formed the silent foundation upon which the scientific edifice of evapotranspiration would eventually be built.

The transition from practical knowledge to scientific inquiry began in earnest during the 17th and 18th centuries as the scientific revolution encouraged natural philosophers to measure and explain the world around them. Early attempts to understand the water cycle often focused on evaporation from water bodies. In 1687, Edmond Halley, better known for his comet, conducted one of the first quantitative experiments on evaporation. He set up a pan of water under controlled conditions and measured its weight loss over time, providing some of the first experimental evidence for the role of solar radiation and wind in driving evaporation. However, these early experiments largely overlooked the contribution of vegetation, treating plants as passive elements in the landscape. The scientific community of the time was still grappling with basic questions about whether plants actually drew water from the soil or somehow generated it internally, a debate that would not be fully resolved until the meticulous experiments of the following century.

The intellectual scaffolding for modern evapotranspiration science truly began to take shape in the early 19th century with the work of John Dalton. In 1802, building on his own law of partial pressures, Dalton published his pioneering work on evaporation, proposing that the rate of evaporation is proportional to the difference between the vapor pressure at the evaporating surface and the vapor pressure in the overlying air. This simple yet profound insight identified the fundamental driving force for evaporation: what we now call the vapor pressure deficit (VPD). Dalton's formulation,  $E = C(e_s - e_a)$ , where  $E$  is the evaporation rate,  $(e_s - e_a)$  is the vapor pressure deficit, and  $C$  is a coefficient dependent on wind speed, represented a monumental leap from qualitative description to quantitative, physics-based explanation. While his work focused primarily on open water evaporation, it provided the essential theoretical framework that would later be adapted and expanded to include the biological complexities of transpiration. For the first time, scientists had a mathematical equation that could predict evaporation rates based on measurable atmospheric variables, laying a cornerstone for all future evapotranspiration modeling.

The next crucial step forward came from the often-overlooked work of Wilhelm Schmidt in the early 20th century. While Dalton had identified the atmospheric demand, Schmidt's studies on boundary layers in the 1920s revealed the critical bottleneck that controls how efficiently that demand can be met. He demonstrated that a thin layer of relatively still air clings to any surface, whether a soil particle or a leaf, and that water vapor must slowly diffuse through this boundary layer to reach the turbulent atmosphere beyond. Schmidt's work showed that the thickness of this layer, which is influenced by surface roughness and wind speed, acts as a critical resistance to water vapor transfer. This concept of aerodynamic resistance was revolutionary, explaining why, for instance, evaporation from a rough forest canopy is often more efficient than from a smooth water surface under identical weather conditions. Schmidt's insights into the physics of the air-surface interface provided the missing piece of the aerodynamic puzzle that Howard Penman would later masterfully integrate into his combination equation.



The year 1948 marks a watershed moment in the history of evapotranspiration science with the publication of Howard Penman's seminal paper, "Natural Evaporation from Open Water, Bare Soil and Grass." Working at the Rothamsted Experimental Station in England, Penman achieved what many had thought impossible: he derived a single equation that could estimate evaporation by combining the two fundamental requirements for the process—the supply of energy (primarily from net radiation) and the removal of water vapor (through aerodynamic transport). The Penman equation elegantly balanced the energy available to change liquid water into vapor with the atmosphere's capacity to carry that vapor away. It was a conceptual tour de force that synthesized the work of his predecessors, incorporating Dalton's vapor pressure deficit concept and Schmidt's boundary layer resistance into a unified, physically-based framework. Unlike earlier empirical methods that were calibrated for specific locations, Penman's equation had universal applicability, founded as it was on the unchanging laws of physics. It quickly became the gold standard for estimating potential evapotranspiration and remains the theoretical foundation for most modern ET models today.

While Penman's equation was revolutionary, it still treated the surface as a simple, uniform wet surface. The biological reality of vegetation regulation required another conceptual leap, which came in 1965 from John Monteith. Building directly on Penman's work, Monteith recognized that plants, through their stomata, could actively control the rate at which they release water vapor. He introduced the concept of surface resistance (or canopy resistance) into Penman's equation, creating what we now know as the Penman-Monteith equation. This single resistance term captured the complex biological responses of vegetation to its environment, including the effects of light, carbon dioxide concentration, temperature, and water stress on stomatal aperture. Monteith's transformation of the Penman equation was a stroke of genius that bridged the gap between physical meteorology and plant physiology. It allowed the same fundamental equation to be applied not just to water and wet grass, but to any vegetated surface—from a wheat field to a tropical rainforest—by properly parameterizing this surface resistance. This advancement made it possible to move beyond the concept of potential evapotranspiration and model actual, biologically-controlled water use from real-world ecosystems.

The evolution of understanding during this period was also marked by the emergence of the soil-plant-atmosphere continuum (SPAC) concept in the 1960s and 1970s, largely championed by scientists like John Philip. This idea represented a paradigm shift in how scientists viewed water movement. Rather than seeing soil, plant, and atmosphere as separate compartments with independent water relations, the SPAC concept envisioned water as moving along a continuous potential gradient, much like water flowing through a series of connected pipes. Water potential decreased progressively from the relatively wet soil, through the plant's vascular system, to the extremely dry air of the atmosphere, with each step offering its own unique resistance. This holistic view helped scientists understand why a plant might wilt not just because the soil was dry, but because the atmospheric demand was so intense that the plant could not draw water quickly enough to replace what was lost through its leaves. The SPAC framework integrated plant physiology, soil physics, and micrometeorology into a single, coherent system, providing the conceptual basis for the sophisticated process-based models that would follow.

The final decades of the 20th century witnessed two more major breakthroughs that transformed evapotranspiration science from a research discipline into a widely applied tool. The first was the standardization effort

led by the Food and Agriculture Organization (FAO) of the United Nations. Recognizing the need for a globally consistent method for crop water management, the FAO convened expert panels throughout the 1970s, 1980s, and 1990s to evaluate and recommend the best methods for calculating reference evapotranspiration. In 1998, they published their definitive report, formally adopting the FAO Penman-Monteith equation as the sole standard method. This decision created a common language for agronomists, irrigation engineers, and water managers worldwide, enabling the sharing of data and the development of crop coefficients that could be applied with confidence across diverse climates and cropping systems.

The second transformative breakthrough was the emergence of satellite-based remote sensing in the 1980s and 1990s. The launch of satellites like Landsat in the 1972 and later the MODIS sensors in 1999 provided, for the first time, a way to observe key variables related to evapotranspiration across vast areas. Scientists could now measure surface temperature (a key indicator of evaporative cooling), vegetation greenness (related to transpiration capacity), and albedo (related to energy absorption) on a global scale. This led to the development of energy balance models like SEBAL and METRIC, which used satellite thermal imagery to estimate actual evapotranspiration on a pixel-by-pixel basis. This technological leap moved evapotranspiration science beyond the limitations of point measurements from lysimeters or flux towers, allowing for the creation of

### 1.3 Physical Principles and Mechanisms

comprehensive evapotranspiration maps that could guide water management decisions across entire watersheds and even continents. This technological revolution, while transformative, rests upon a deep understanding of the physical principles that govern evapotranspiration—principles that we must now examine in detail to appreciate both the elegance of nature’s design and the sophistication of our attempts to model it.

#### 1.3.1 3.1 Energy Balance Fundamentals

At its most fundamental level, evapotranspiration is an energy conversion process, transforming solar energy into latent heat stored in water vapor. This transformation follows the immutable laws of thermodynamics, particularly the conservation of energy, which demands that energy entering a system must either be stored, transformed, or transferred elsewhere. For any land surface, this relationship is captured in the surface energy balance equation:  $R_n = LE + H + G + \Delta S$ , where  $R_n$  represents net radiation (the primary energy input),  $LE$  is the latent heat flux (energy used for evapotranspiration),  $H$  is the sensible heat flux (energy warming the air),  $G$  is the ground heat flux (energy warming the soil), and  $\Delta S$  represents energy stored in the vegetation canopy or photosynthesized as chemical energy. This elegant equation, simple in appearance yet profound in its implications, serves as the foundation for virtually all modern evapotranspiration models.

Net radiation, the engine driving the entire system, represents the balance between incoming and outgoing radiation at the Earth’s surface. During daylight hours, shortwave radiation from the sun dominates, with its intensity varying according to latitude, season, time of day, and atmospheric conditions. A typical summer day might deliver 600-800 watts per square meter of solar radiation to a horizontal surface at midday in

temperate latitudes, though this can exceed 1000 watts per square meter in tropical clear-sky conditions. Not all this energy is absorbed; a portion is reflected based on the surface albedo, which ranges from 0.05 for dark water to 0.85 for fresh snow. Simultaneously, the surface emits longwave infrared radiation proportional to its temperature, while receiving longwave radiation from the atmosphere and clouds. The net result of these four radiation streams determines the energy available to power evapotranspiration. The remarkable efficiency of this natural energy system is perhaps best appreciated by considering that approximately 80% of solar energy reaching vegetated land surfaces is ultimately returned to the atmosphere as latent heat through evapotranspiration, making it the largest energy flux in most terrestrial ecosystems.

The latent heat of vaporization, the energy required to transform liquid water into vapor at a given temperature, represents one of nature's most significant energy storage mechanisms. At 20°C, this value stands at approximately 2.45 megajoules per kilogram of water evaporated—a substantial amount of energy that is effectively “hidden” in water vapor until it condenses elsewhere. This energy storage mechanism makes evapotranspiration a critical component of Earth's climate regulation system. To appreciate the scale of this energy transport, consider that the Amazon rainforest alone evaporates approximately 20 trillion tons of water annually, storing and transporting roughly  $5 \times 10^{22}$  joules of energy—equivalent to the total energy consumption of human civilization for more than a decade. This latent heat transport moderates tropical temperatures while warming higher latitudes when the vapor eventually condenses into clouds and precipitation, creating a global atmospheric heat engine that redistributes solar energy from equator to poles.

The partitioning of available energy between latent and sensible heat fluxes reveals fascinating insights into ecosystem behavior and water availability. When water is abundant, as in well-watered agricultural fields or natural wetlands, the majority of net radiation typically goes into evapotranspiration, creating high LE fluxes and relatively low sensible heat fluxes. This scenario results in cooler surface temperatures and higher humidity, creating a more moderate microclimate. Conversely, when water becomes limiting, as during droughts or in arid environments, the energy balance shifts dramatically toward sensible heat flux. The surface temperature rises, sometimes by 10-20°C compared to well-watered conditions, while evapotranspiration rates plummet. This shift creates a positive feedback loop: higher temperatures increase atmospheric demand for water vapor, further stressing vegetation and potentially accelerating drought conditions. The ability of ecosystems to maintain high evapotranspiration rates under water stress—what scientists call “isohydric” versus “anisohydric” behavior—has emerged as a critical factor in determining forest vulnerability to climate change, with isohydric species that strictly regulate water use often showing greater resistance to drought-induced mortality.

The ground heat flux, while typically smaller than LE and H in most vegetated ecosystems, plays a crucial role in the diurnal and seasonal patterns of evapotranspiration. During morning hours, as the sun rises, a portion of incoming radiation warms the soil surface, creating a downward heat flux that can temporarily reduce energy available for evapotranspiration. This stored soil heat is released later in the day and during nighttime, maintaining some evapotranspiration even after sunset and smoothing the diurnal cycle of water loss. In high-latitude ecosystems with permafrost, the ground heat flux becomes particularly significant, as even small changes in energy balance can determine whether permafrost thaws, with profound implications for landscape stability and carbon release. The seasonal storage and release of heat in soil and water bodies

represents one of Earth's natural thermal regulators, buffering temperature changes and maintaining more consistent evapotranspiration rates than would occur if all energy were immediately partitioned between LE and H.

### 1.3.2 3.2 Mass Transfer Principles

While energy provides the potential for evapotranspiration, mass transfer principles determine how efficiently that potential can be realized. The movement of water vapor from evaporating surfaces to the free atmosphere follows the fundamental laws of diffusion and turbulent transport, with the rate of transfer proportional to the concentration gradient and inversely proportional to the resistance encountered along the pathway. This relationship, first mathematically described by Adolf Fick in 1855, forms the theoretical basis for understanding how atmospheric conditions control evapotranspiration rates. In the context of evapotranspiration, the concentration gradient is expressed as the vapor pressure deficit—the difference between the saturation vapor pressure at the evaporating surface temperature and the actual vapor pressure of the overlying air.

Vapor pressure deficit represents perhaps the single most important atmospheric driver of evapotranspiration after energy availability. When VPD is low, indicating that the air is already close to saturation, the gradient driving water vapor movement is weak, and evapotranspiration rates decline regardless of available energy. This explains why tropical rainforests, despite receiving abundant energy, don't evaporate water indefinitely—the high humidity created by their own transpiration eventually limits further water loss. Conversely, in hot, dry conditions, VPD can become extremely high, creating powerful evaporative demand that can rapidly deplete soil moisture and stress vegetation. The relationship between VPD and evapotranspiration is not linear; as VPD increases beyond certain thresholds, many plants respond by closing their stomata to prevent excessive water loss, introducing biological regulation into what would otherwise be a purely physical process. This plant response to VPD has emerged as a critical factor in forest mortality events during extreme drought and heat waves, highlighting the complex interplay between atmospheric demand and biological control.

Aerodynamic resistance theory, building on the boundary layer concepts introduced by Wilhelm Schmidt, provides the framework for understanding how atmospheric conditions control the efficiency of water vapor transfer. The resistance pathway from evaporating surface to the free atmosphere consists of several components in series, each presenting its own unique challenges to water vapor movement. The first barrier is the quasi-laminar boundary layer adhering to the evaporating surface, whether that be a soil particle, a leaf, or a water body. Within this thin layer, typically only millimeters thick, water vapor moves primarily by molecular diffusion—a slow process compared to the turbulent mixing that dominates beyond the boundary layer. The thickness of this layer depends primarily on wind speed and surface roughness; higher winds create more turbulent conditions that thin the boundary layer, while smoother surfaces allow thicker layers to develop. This explains why evaporation from rough, textured surfaces like forests often exceeds that from smooth water surfaces under identical weather conditions—the increased turbulence enhances the efficiency of water vapor removal.

Beyond the surface boundary layer, water vapor must navigate through the increasingly turbulent atmospheric surface layer, typically extending 10-100 meters above the ground depending on atmospheric stability. In this region, transfer occurs through the chaotic mixing of air parcels, with the rate of transfer proportional to the friction velocity—a measure of turbulent intensity that depends primarily on wind speed and surface roughness. The relationship between wind speed and evapotranspiration is complex and non-linear; at very low wind speeds, increasing wind dramatically enhances evapotranspiration by efficiently removing saturated air from the surface. However, beyond certain wind speeds, the relationship weakens as other factors become limiting. This nuanced relationship explains why, for instance, evapotranspiration rates often plateau during very windy conditions despite continued increases in wind speed.

The wind profile itself follows a logarithmic pattern with height above the surface, a relationship first described by Ludwig Prandtl in the 1920s that remains fundamental to micrometeorology today. This logarithmic profile reflects the increasing influence of surface friction with decreasing height, creating a gradient of wind speeds that becomes steeper over smoother surfaces and gentler over rougher ones. The mathematical description of this profile requires two key parameters: roughness length ( $z_0$ ), representing the height above the surface at which wind speed theoretically becomes zero, and displacement height ( $d$ ), representing the height at which the wind profile is effectively “displaced” upward by vegetation or other obstacles. For short grass, roughness length might be only 0.01 meters, while for a dense forest it could exceed 1 meter. These parameters, while seemingly technical, have profound implications for evapotranspiration rates, as they determine how efficiently atmospheric turbulence can penetrate the canopy and remove water vapor from transpiring leaves.

Atmospheric stability introduces another layer of complexity to mass transfer processes. When the surface is warmer than the overlying air, as typically occurs during daytime over land, conditions become unstable, promoting vigorous turbulent mixing that enhances evapotranspiration. Conversely, when the surface is cooler than the air, as often occurs at night or during advection of warm air over cold water, stable conditions suppress turbulence, creating a strong inversion layer that can dramatically reduce evapotranspiration rates. These stability effects are quantified using the Richardson number or Monin-Obukhov similarity theory, which incorporate both thermal and mechanical contributions to turbulence. The practical implications are substantial; for instance, nighttime evapotranspiration from forests can continue at significant rates when atmospheric conditions remain unstable, while stable conditions can essentially shut down evapotranspiration even when the surface remains wet. Understanding these stability effects has become crucial for interpreting eddy covariance measurements and for improving the accuracy of evapotranspiration models, particularly during transitional periods around sunrise and sunset when stability changes rapidly.

### 1.3.3 3.3 Aerodynamic Considerations

The aerodynamic properties of surfaces fundamentally control how efficiently they exchange heat, mass, and momentum with the atmosphere, making them central to understanding evapotranspiration processes. Surface roughness, perhaps the most important aerodynamic characteristic, determines how effectively atmospheric turbulence can penetrate the canopy and reach evaporating surfaces. This roughness is not merely

a visual characteristic but a complex aerodynamic property that depends on vegetation height, density, flexibility, and spatial arrangement. A forest with a complex multi-layered canopy presents vastly different aerodynamic resistance than a uniform agricultural crop of similar height, despite their comparable roughness lengths. This complexity explains why simple height-based roughness estimates often fail to capture the true aerodynamic behavior of natural vegetation, leading to errors in evapotranspiration estimates that can exceed 30% in some cases.

Roughness length and displacement height, while often treated as static parameters, actually vary dynamically with wind speed, vegetation phenology, and even within-canopy humidity conditions. During growing seasons, as crops develop from seedlings to mature plants, roughness length can increase by orders of magnitude, fundamentally altering the surface-atmosphere exchange characteristics. Similarly, deciduous forests experience dramatic seasonal changes in aerodynamic properties as leaves emerge in spring and fall in autumn. Even within a single day, the effective roughness can change as leaves wilt under water stress or as wind speed increases and vegetation elements become more streamlined. These dynamic variations in aerodynamic parameters represent one of the greatest challenges in accurate evapotranspiration modeling, requiring sophisticated approaches that can capture the feedback between vegetation condition and atmospheric exchange.

The vertical structure of vegetation canopies creates particularly complex aerodynamic environments that profoundly influence transpiration rates. Within dense canopies, wind speeds typically decrease exponentially with depth following the extinction coefficient principle, with the rate of decline determined by leaf area density distribution. This creates a vertical gradient in aerodynamic resistance, with leaves deep within the canopy experiencing much less efficient water vapor removal than those near the top. However, these sheltered leaves also experience reduced radiation and VPD, creating a complex balance of factors that determines their contribution to whole-canopy transpiration. The wind profile modification within canopies also affects the deposition of pollutants, the dispersal of pollen and spores, and the microclimate experienced by understory organisms, demonstrating how aerodynamic considerations extend far beyond their influence on evapotranspiration.

Different land cover types present remarkably diverse aerodynamic challenges that must be accounted for in evapotranspiration models. Water bodies, with their smooth surfaces, typically have very low roughness lengths (0.0001-0.001 meters) and negligible displacement heights, resulting in high aerodynamic resistance that limits evaporation despite abundant water availability. Urban areas present the opposite extreme, with buildings creating complex flow patterns that can either enhance or suppress evapotranspiration depending on wind direction and urban geometry. Agricultural fields fall somewhere in between, with their aerodynamic properties heavily influenced by row orientation, planting density, and crop architecture. The emergence of precision agriculture has revealed that even small variations in planting patterns can create detectable differences in field-scale evapotranspiration patterns, highlighting the importance of accounting for fine-scale aerodynamic heterogeneity.

Atmospheric stability corrections represent one of the most technically challenging yet essential aspects of aerodynamic considerations in evapotranspiration modeling. When conditions deviate from neutral stability,



the logarithmic wind profile must be modified using stability functions that depend on the Monin-Obukhov length—a parameter that incorporates both thermal and mechanical turbulence effects. These corrections can change aerodynamic resistance by factors of 2-3 or more, particularly during early morning and evening transitional periods when stability changes rapidly. The mathematical formulation of these corrections has been the subject of extensive research since the 1950s, with various functions proposed by different research groups. The implementation of these corrections in operational evapotranspiration models represents a significant challenge, as they require iterative calculations and careful handling of near-neutral conditions where numerical instabilities can arise.

### 1.3.4 3.4 Soil-Plant-Atmosphere Continuum

The soil-plant-atmosphere continuum (SPAC) concept represents one of the most paradigm-shifting advances in our understanding of evapotranspiration, reframing water movement not as a series of disconnected processes but as a continuous flow along a potential gradient. This holistic view, championed by John Philip and others in the 1960s, revealed that water moves from relatively wet soil through the plant vascular system to extremely dry atmospheric air, with each step presenting its unique resistance characteristics. The driving force for this movement is water potential, measured in megapascals, which decreases progressively along this pathway from typically -0.01 to -0.1 MPa in moist soil, to -0.5 to -2 MPa in plant xylem, to -10 to -100 MPa in the atmosphere. This gradient represents one of the steepest potential differences in nature, with atmospheric demand often exceeding soil supply by orders of magnitude during hot, dry conditions.

Root water uptake mechanisms represent the critical first step in the SPAC, determining how effectively plants can access soil moisture reserves. The process begins at the root-soil interface, where root hairs dramatically increase the surface area for water absorption while creating intimate contact with soil particles. Water moves from soil into roots primarily through the apoplastic pathway (between cells) in the root cortex, then must cross the selectively permeable endodermis to enter the vascular system. This crossing represents a major resistance point, regulated by aquaporins—protein channels that can open or close in response to environmental conditions. The discovery of aquaporins in the early 1990s revolutionized our understanding of root water uptake, revealing that plants could dynamically regulate their hydraulic conductivity rather than being passive conduits. This regulatory capacity allows plants to maintain water uptake even as soil dries, though at the cost of increased metabolic energy expenditure.

The spatial distribution of roots creates another layer of complexity in water uptake dynamics. Most plants develop a dual root system: shallow lateral roots that quickly capture rainfall and deeper taproots that provide access to more stable moisture reserves during drought. This architectural strategy allows plants to buffer against the high variability of soil moisture in the upper layers while maintaining access to deeper water when needed. The relative contribution of different soil depths to total water uptake changes dramatically as soils dry, with

## 1.4 Direct Measurement Techniques

The sophisticated understanding of evapotranspiration processes that has emerged through decades of research would remain merely theoretical without the ability to measure these fluxes directly in the field. The challenge of quantifying the invisible movement of water from land to atmosphere has driven remarkable innovations in measurement technology, from massive weighing lysimeters that can detect water loss equivalent to a few millimeters of rainfall to sonic anemometers that measure wind speeds thousands of times per second. These direct measurement techniques not only provide the ground truth against which all models are validated but also continue to reveal new insights into the complex controls on evapotranspiration. Each method offers a unique window onto different aspects of the evapotranspiration process, and together they form a comprehensive toolkit that allows researchers to peel back the layers of complexity in this fundamental Earth system process.

### 1.4.1 4.1 Lysimetry Systems

Lysimetry represents perhaps the most intuitive approach to measuring evapotranspiration: if you want to know how much water a piece of land is losing to the atmosphere, simply weigh it before and after. The elegance of this concept belies the engineering challenges involved in creating a system that can accurately measure the water balance of a substantial volume of soil while maintaining the environmental conditions necessary for normal plant growth. Modern weighing lysimeters are engineering marvels that can detect changes in mass equivalent to just 0.01 millimeters of water depth—roughly the thickness of a human hair—while supporting several tons of soil and vegetation. These precision instruments typically consist of a large container (often 2-5 meters in diameter and 1-3 meters deep) filled with undisturbed soil that is lifted from the field and placed on a sensitive weighing system. The entire assembly is then installed back in the ground, with the rim of the lysimeter flush with the surrounding soil surface, creating an environment that closely mimics natural conditions.

The historical development of lysimetry traces back to the early 20th century, though crude versions existed earlier. The first scientific lysimeters were essentially large buckets filled with soil, weighed periodically with mechanical scales to determine water loss. These early systems suffered from numerous problems: edge effects where the lysimeter soil behaved differently from surrounding soil, poor temperature control that affected measurement accuracy, and disruption of natural root growth patterns. The breakthrough came in the 1950s and 1960s with the development of electronic load cells that could provide continuous, high-precision measurements. One of the most famous early installations was the Coshocton lysimeter facility in Ohio, established in 1937, which featured massive monolith lysimeters carved directly from the native soil profile. These instruments provided some of the first continuous measurements of evapotranspiration in the United States and helped establish fundamental patterns of crop water use that still guide irrigation scheduling today.

Modern weighing lysimeters have evolved into sophisticated environmental monitoring stations. The most advanced systems, such as those at the Terrestrial Environmental Observatories in Germany, incorporate



not only precision weighing but also extensive sensor arrays that measure soil moisture at multiple depths, soil temperature, radiation balance, and meteorological conditions above the canopy. Some even include automated rainout shelters that can exclude precipitation to study the response of vegetation to drought conditions. The data from these systems has revealed fascinating details about evapotranspiration dynamics that were previously invisible to researchers. For instance, lysimeter measurements have shown that many crops continue to transpire at significant rates during nighttime, particularly when atmospheric conditions remain unstable and soil moisture is abundant. This nocturnal transpiration, once thought to be negligible, can account for 5-15% of daily water loss in some species, challenging our understanding of plant water relations.

Drainage lysimeters represent an alternative approach that focuses on the water balance rather than direct mass change. These systems, also known as non-weighing lysimeters, are equipped with collection systems at the bottom that measure water draining through the soil profile. By carefully accounting for all inputs (precipitation, irrigation) and outputs (drainage, surface runoff), evapotranspiration can be calculated as the residual term in the water balance equation. While generally less accurate than weighing lysimeters, drainage lysimeters are considerably less expensive and can be installed in larger numbers, making them valuable for studying spatial variability in evapotranspiration across different soil types or vegetation communities. The lysimeter facility at the University of California, Davis, for example, operates dozens of drainage lysimeters studying water use by different California native plant species, providing crucial data for restoration ecology and urban landscaping in water-limited environments.

The precision requirements for lysimeter measurements are extraordinary and highlight the engineering challenges involved. A typical agricultural field might lose 5-10 millimeters of water per day through evapotranspiration during peak growing season. To capture the diurnal pattern of this loss with reasonable resolution, a lysimeter must be able to detect changes of 0.1 millimeters or less—equivalent to a mass change of just 1-2 kilograms for a 10-square-meter lysimeter. This level of precision requires careful consideration of temperature effects on the weighing system, wind loading on the vegetation, and even the gravitational effects of lunar tides, which can cause apparent mass changes of several kilograms in the largest lysimeters. The most sophisticated systems employ multiple load cells in a Wheatstone bridge configuration to minimize these errors, along with temperature-controlled housings and sophisticated data processing algorithms that filter out noise while preserving the true signal of evapotranspiration.

#### **1.4.2 4.2 Eddy Covariance Technology**

The eddy covariance method represents a revolutionary approach to measuring evapotranspiration that emerged from advances in micrometeorology and electronics in the late 20th century. Rather than measuring the integrated water balance of a surface, eddy covariance directly measures the vertical flux of water vapor by simultaneously observing the rapid fluctuations in vertical wind speed and water vapor concentration. The method relies on the fundamental principle that the vertical transport of any scalar quantity (such as water vapor, heat, or carbon dioxide) occurs through turbulent eddies in the atmosphere. By measuring the covariance between vertical wind speed and water vapor concentration, we can directly determine the flux of

water vapor moving upward or downward at the measurement point. This elegant approach, first proposed in the 1950s but only made practical by modern electronics in the 1980s, provides what is arguably the most direct measurement of evapotranspiration available today.

The instrumentation requirements for eddy covariance are demanding and reflect the technical challenges of measuring rapid atmospheric fluctuations. A typical eddy covariance system consists of a three-dimensional sonic anemometer that measures wind speed and temperature at frequencies of 10-20 Hz, combined with a fast-response gas analyzer that measures water vapor concentration at similar rates. The sonic anemometer works by sending ultrasonic pulses between transducers arranged in a three-dimensional pattern; the time it takes for these pulses to travel provides precise measurements of wind speed along each axis. Modern gas analyzers use either infrared absorption (for water vapor and carbon dioxide) or laser-based techniques to achieve the necessary response time. The entire system must be carefully leveled and oriented, with the measurement height typically 2-3 times the vegetation height to ensure that the measurements are within the constant flux layer where assumptions about steady-state conditions are valid.

The data processing requirements for eddy covariance are substantial and have driven the development of sophisticated software and protocols. Raw data from eddy covariance systems contains noise from various sources, including instrument drift, signal interference, and non-turbulent atmospheric motions. Researchers must apply numerous corrections to these data, including coordinate rotations to align the measurements with the mean wind flow, corrections for density fluctuations (the Webb-Pearman-Leuning correction), and quality control procedures to identify and remove periods when assumptions are violated. The FLUXNET network, established in the 1990s to coordinate eddy covariance measurements worldwide, has developed standardized processing pipelines that ensure consistency across hundreds of sites. This standardization has been crucial for creating global datasets of evapotranspiration that can be used to evaluate satellite products and improve Earth system models.

One of the most powerful aspects of the eddy covariance method is its ability to simultaneously measure multiple fluxes. The same instrument package that measures water vapor flux can also measure carbon dioxide flux, sensible heat flux, and momentum flux, providing a comprehensive picture of the surface-atmosphere exchange. This integrated measurement capability has led to fundamental discoveries about the coupling between carbon and water cycles in ecosystems. For example, eddy covariance measurements have revealed that the water use efficiency of forests (the ratio of carbon uptake to water loss) varies systematically with climate, with tropical rainforests being more efficient than previously thought while some temperate forests are less efficient. These findings have important implications for understanding how ecosystems will respond to climate change and for predicting future land-atmosphere feedbacks.

The footprint concept represents a critical consideration in interpreting eddy covariance measurements. Unlike lysimeters, which measure evapotranspiration from a defined surface area, eddy covariance measurements integrate contributions from upwind areas, with the relative contribution of different locations depending on wind speed, atmospheric stability, and measurement height. This footprint typically extends hundreds of meters upwind, with the exact shape and size determined by complex mathematical functions. Researchers must carefully consider this footprint when selecting sites and interpreting results, particularly

in heterogeneous landscapes where different land cover types might contribute to the measured flux. Advanced footprint models now allow researchers to create footprint-weighted maps of the contributing area, helping to ensure that the measured fluxes are representative of the ecosystem of interest.

The global network of eddy covariance towers has transformed our understanding of evapotranspiration across biomes and climate zones. With over 1000 sites worldwide contributing data to FLUXNET, researchers have been able to identify general patterns in ecosystem water use that were previously impossible to discern. These measurements have shown, for instance, that evapotranspiration from tropical rainforests is often less than potential evapotranspiration due to frequent cloud cover that reduces incoming radiation, while some semi-arid ecosystems can maintain surprisingly high evapotranspiration rates through deep-rooted vegetation that accesses groundwater. The long-term records from some sites, now extending over two decades, are beginning to reveal trends in evapotranspiration that may be related to climate change, though separating climate signals from vegetation dynamics remains a significant challenge.

### 1.4.3 4.3 Sap Flow Measurements

While lysimeters and eddy covariance systems measure total evapotranspiration, sap flow techniques provide a window specifically on the transpiration component by measuring water movement within individual plants. This approach, based on the principle that transpiration drives water flow through the plant's vascular system, allows researchers to directly observe how individual plants respond to environmental conditions and water stress. The development of sap flow methods has revolutionized plant physiology by making it possible to continuously monitor transpiration from individual trees, shrubs, and crops over periods of weeks to months. These measurements have revealed the remarkable diversity of water use strategies among different species and have provided crucial insights into how forests and other ecosystems regulate their water use.

The heat pulse velocity method, one of the earliest sap flow techniques, was developed in the 1950s but only became widely used with advances in electronics in the 1980s. This method works by briefly heating a small section of the stem with a needle-like heater and then measuring the time it takes for this heat pulse to reach temperature sensors located upstream and downstream. The velocity of this heat pulse is related to the water flow rate in the xylem, though the relationship is complex and depends on wood anatomy, thermal properties, and the arrangement of sensors. Modern heat pulse systems can measure sap flow with accuracies of 10–15% in suitable species, though they work best in trees with relatively uniform xylem structure. The method has been particularly valuable for studying water use in forest trees, where it has revealed that individual trees can transpire hundreds of liters of water per day during peak growing season—equivalent to several household water tanks.

The thermal dissipation technique, developed by Granier in the 1980s, represents a simpler but equally powerful approach to sap flow measurement. This method uses two temperature probes inserted into the sapwood: one continuously heated with a constant power source and another unheated reference probe. The temperature difference between these probes depends on how quickly the flowing sap removes heat from the heated probe, with higher sap flow resulting in smaller temperature differences. Granier sensors are

relatively inexpensive, require minimal power, and can be left unattended for months, making them ideal for long-term monitoring in remote locations. The simplicity and robustness of this approach have led to its widespread adoption, with thousands of Granier sensors now deployed worldwide studying everything from water use in Amazonian rainforests to irrigation scheduling in vineyards.

Scaling sap flow measurements from individual plants to ecosystem-level transpiration presents significant methodological challenges that have driven the development of sophisticated scaling approaches. The fundamental problem is that sap flow measurements represent point measurements within individual plants, while ecosystem transpiration integrates across all plants of different sizes, species, and microsite conditions. Researchers have developed various scaling strategies, including allometric relationships that relate sap flow to tree diameter or leaf area, and statistical sampling approaches that measure a representative subset of individuals and extrapolate to the entire stand. The most successful scaling studies combine sap flow measurements with detailed characterization of stand structure, often using remote sensing to map leaf area index and species composition. These integrated approaches have shown that transpiration from forests can vary by factors of 2-3 even within the same climate zone, depending on species composition, stand age, and soil water availability.

Sap flow measurements have revealed fascinating insights into plant water use strategies that were invisible to earlier measurement techniques. Perhaps most surprisingly, these measurements have shown that many plants continue to transpire at night, with nocturnal fluxes often reaching 10-20% of daytime rates in some species. This nighttime transpiration, once thought to be negligible, appears to serve several functions: it may help redistribute water within the plant, support nighttime metabolism, or prepare the plant for rapid morning transpiration. Sap flow studies have also revealed remarkable diversity in drought responses among co-occurring species, with some trees maintaining relatively constant transpiration by accessing deep soil water while others rapidly reduce water loss in response to drying conditions. These different strategies have important implications for forest resilience to climate change and for predicting species composition shifts under future drought conditions.

The technical challenges of sap flow measurement vary dramatically among different plant types, leading to the development of specialized methods for different applications. For herbaceous crops and small shrubs, the stem heat balance method provides accurate measurements by heating the entire stem and accounting for all heat losses. For palms and other monocots with diffuse vascular systems, special sensor arrangements are needed to capture flow in scattered vascular bundles. In very large trees, where installing sensors at breast height can be impractical, researchers have developed methods to estimate transpiration from branch-level measurements or from measurements of trunk diameter fluctuations, which are related to water storage dynamics. Each of these specialized approaches has expanded the range of ecosystems where transpiration can be directly measured, contributing to our understanding of water use across diverse plant communities.

#### **1.4.4 4.4 Bowen Ratio and Energy Balance Methods**

The Bowen ratio method offers an elegant approach to estimating evapotranspiration by partitioning the available energy between sensible and latent heat fluxes. Named after Ira Bowen, who developed the concept

in 1926, this method relies on the principle that the ratio of sensible to latent heat fluxes (the Bowen ratio,  $\beta = H/LE$ ) is equal to the ratio of the vertical gradients of temperature and water vapor, multiplied by the psychrometric constant. By measuring temperature and humidity at two heights above the surface, we can calculate the Bowen ratio and then use it to partition the available energy (determined from radiation balance and soil heat flux measurements) between sensible and latent heat. This approach, while conceptually simple, requires careful attention to measurement accuracy and represents one of the most reliable methods for estimating evapotranspiration when eddy covariance systems are not available.

The instrumentation requirements for Bowen ratio measurements are relatively modest compared to eddy covariance, making this method attractive for long-term monitoring in remote locations. A typical Bowen ratio system consists of two sets of temperature and humidity sensors mounted at different heights above the vegetation, usually separated by 1-2 meters. These sensors must be carefully matched and calibrated, as the method is sensitive to small differences between the upper and lower measurements. Modern systems use fine-wire thermocouples for temperature measurements and chilled-mirror hygrometers for humidity, both of which can provide the necessary precision. In addition to the profile measurements, a Bowen ratio system requires measurements of net radiation (using a net radiometer) and soil heat flux (using heat flux plates buried at several depths). The entire system can be powered by solar panels and data logged for extended periods, making it suitable for deployment in remote ecosystems from deserts to tundra.

The Bowen ratio method performs best under conditions where the assumption of equal turbulent transfer coefficients for heat and water vapor is valid. This assumption generally holds well for neutral to slightly unstable atmospheric conditions, which typically occur during much of the daytime over vegetated surfaces. However, during very stable conditions (often at night) or very unstable conditions (during intense solar heating), the transfer coefficients can diverge, introducing errors into the calculations. Researchers have developed various corrections for these situations, though the method becomes increasingly unreliable as stability deviates from neutral conditions. Another limitation occurs when the Bowen ratio approaches -1, which happens when sensible and latent heat fluxes are equal in magnitude but opposite in direction. Under these conditions, small measurement errors can lead to large uncertainties in the calculated fluxes, and many researchers apply quality control filters to exclude data when the Bowen ratio falls within critical ranges.

Despite these limitations, the Bowen ratio method has provided valuable long-term records of evapotranspiration from diverse ecosystems. One of the longest continuous records comes from the Konza Prairie Biological Station in Kansas, where Bowen ratio systems have been measuring evapotrans

## 1.5 Empirical Models

The sophisticated measurement techniques described in the previous section, while providing invaluable insights into evapotranspiration processes, remain limited in their spatial and temporal coverage. The logistical challenges and costs associated with installing and maintaining lysimeters, eddy covariance towers, and sap flow systems mean that direct measurements can only be obtained at relatively few locations. This fundamental limitation has driven the development of empirical models—mathematical relationships that estimate evapotranspiration from more readily available meteorological variables. These models, born from

necessity in an era before computers and satellite observations, continue to play important roles in water management today, particularly in regions where comprehensive weather data remain unavailable or where simplicity outweighs the need for precision.

Temperature-based methods represent perhaps the oldest and most intuitive approach to estimating evapotranspiration, built on the fundamental relationship between temperature and the energy available for water phase change. The Thornthwaite equation, developed by C. Warren Thornthwaite in 1948, stands as a landmark achievement in this category. Thornthwaite, working with limited data from weather stations across the United States, recognized that mean air temperature could serve as a proxy for the complex energy balance that drives evapotranspiration. His equation incorporated not only temperature but also day length, acknowledging that the same temperature in different seasons or latitudes represents different energy conditions. The Thornthwaite method calculates monthly potential evapotranspiration based on a heat index derived from mean temperature, then adjusts this value based on the actual number of daylight hours in the month. While remarkably simple compared to process-based models, this approach captured enough of the underlying physics to provide reasonable estimates in many temperate regions, particularly for water balance studies where precise daily values were less critical than accurate seasonal totals.

The Hargreaves-Samani equation, published in 1985, represents another milestone in temperature-based modeling that emerged from very different circumstances than Thornthwaite's work. George Hargreaves and Zohrab Samani developed their method while working on agricultural water management projects in developing countries where comprehensive weather data were rarely available. They recognized that even the most basic weather stations typically recorded maximum and minimum temperatures, making these the most universally available meteorological variables. Their elegant formula estimates reference evapotranspiration using only mean temperature and the difference between maximum and minimum temperatures (which serves as a proxy for solar radiation) along with extraterrestrial radiation (which can be calculated from latitude and day of year). The simplicity and data requirements of the Hargreaves-Samani equation have made it one of the most widely used empirical methods worldwide, particularly in regions with limited monitoring infrastructure. Studies have shown that despite its simplicity, this method can achieve accuracy within 15-20% of more complex approaches in many climates, a remarkable achievement given its minimal data requirements.

Linacre's simplified approach, developed by Edward Linacre in the 1970s, offers another perspective on temperature-based estimation. Linacre recognized that temperature alone provided an incomplete picture of evaporative demand, particularly in arid regions where high temperatures might coincide with low humidity and strong advection. His method incorporates temperature along with elevation and latitude to account for variations in atmospheric pressure and solar angle, providing a more physically-based foundation than pure temperature relationships. The Linacre method also includes an adjustment for vegetation type through a factor that accounts for different surface resistances. This approach, while still relatively simple, bridges the gap between purely empirical temperature methods and more physically-based models, demonstrating how empirical relationships can be refined through improved understanding of the underlying processes.

These temperature-based methods share a fundamental limitation: they treat temperature as a proxy for the



complex energy balance that actually drives evapotranspiration. This approximation works reasonably well in many temperate climates where temperature correlates strongly with available energy, but breaks down in situations where energy inputs and temperatures are decoupled. For example, in coastal areas with persistent marine layer influence, temperatures might remain moderate while radiation levels are high, leading temperature-based methods to underestimate evapotranspiration. Similarly, in high-altitude tropical regions, intense solar radiation can drive substantial evapotranspiration despite relatively moderate temperatures. Despite these limitations, temperature-based methods continue to find applications in long-term historical studies, climate change impact assessments, and regions with limited data availability, demonstrating that sometimes the best model is not the most complex one but the one that can actually be applied with available data.

Radiation-based models emerged from the recognition that solar radiation, rather than temperature, represents the primary energy source for evapotranspiration. The Makkink method, developed by Gerrit Makkink in 1957 in the Netherlands, was specifically designed for the cool, humid conditions of Northwestern Europe where cloud cover frequently limits solar radiation. Makkink proposed that reference evapotranspiration could be estimated as a simple proportion of global radiation, typically around 0.65, with this proportion varying with temperature. This relationship emerged from careful analysis of lysimeter data and reflected the observation that in cool climates, a substantial portion of incoming radiation goes into heating the air rather than evaporating water. The Makkink method proved particularly valuable in agricultural planning across Europe and has been incorporated into numerous water management guidelines, though its accuracy declines in arid and semi-arid regions where the relationship between radiation and evapotranspiration differs significantly.

The Turc equation, developed by Ivan Turc in 1961, represents another important contribution to radiation-based modeling with broader geographical applicability. Turc recognized that the efficiency of radiation use for evapotranspiration depends on both temperature and relative humidity, leading him to develop separate equations for humid and arid conditions. In his formulation, potential evapotranspiration is calculated as a function of solar radiation and mean temperature, with a correction factor that depends on relative humidity. This dual approach allowed the Turc equation to maintain reasonable accuracy across diverse climate zones, from the humid conditions of Western Europe to the arid environments of North Africa. The elegance of Turc's method lies in its recognition that the same amount of solar radiation can produce different amounts of evapotranspiration depending on the atmospheric moisture content, a physical reality that simpler radiation-based methods often overlook.

The Priestley-Taylor equation, published in 1972, marked a significant theoretical advance in radiation-based modeling while maintaining relative simplicity. Building on the concept of equilibrium evaporation (the rate that would occur if the atmosphere became saturated through evapotranspiration alone), Priestley and Taylor proposed that actual evapotranspiration typically occurs at about 1.26 times the equilibrium rate. This empirical coefficient emerged from analysis of evaporation measurements from extensive water surfaces and well-watered vegetation, revealing a consistent pattern across different environments. The Priestley-Taylor equation thus requires only measurements of net radiation and temperature (to calculate the slope of the saturation vapor pressure curve), making it considerably simpler than the full Penman equation while

retaining more physical basis than purely empirical methods. This approach has proven particularly valuable for remote sensing applications where net radiation can be estimated from satellite measurements but detailed meteorological data may be unavailable.

Solar radiation estimation techniques have played a crucial role in making radiation-based models applicable in data-sparse regions. When direct measurements of solar radiation are unavailable, which is common in many parts of the world, researchers have developed various approaches to estimate radiation from more commonly measured variables. The Angström-Prescott formula, which relates global radiation to extraterrestrial radiation and the ratio of actual to possible sunshine hours, represents the most widely used approach. This relationship, originally proposed in the 1920s and refined in the 1940s, requires only sunshine duration measurements, which have been made at weather stations for over a century. More recent approaches estimate radiation from temperature range (as in the Hargreaves-Samani method) or from cloud cover observations. These estimation techniques have enabled the application of radiation-based models in historical studies and in regions where radiation monitoring infrastructure is lacking, demonstrating how empirical relationships can fill critical data gaps.

Combination methods attempt to synthesize the strengths of both temperature-based and radiation-based approaches while acknowledging their individual limitations. The Blaney-Criddle formula, developed in the early 1950s by Harry Blaney and Wayne Criddle, represents one of the earliest and most influential combination methods. Working for the U.S. Soil Conservation Service, they developed a practical method for estimating crop water requirements that could be applied by agricultural extension agents with minimal training. Their approach combined temperature data (representing energy availability) with day length (representing the duration of energy input) and crop-specific coefficients to estimate monthly water requirements. The Blaney-Criddle method became the standard for irrigation planning across the western United States for decades and was incorporated into numerous irrigation design guidelines worldwide. While later research revealed systematic errors in certain climates, particularly where advection plays an important role, the method's simplicity and practical focus made it enormously influential in the development of modern irrigation agriculture.

Modified Hargreaves approaches have emerged as researchers sought to improve upon the original temperature-based method while retaining its minimal data requirements. These modifications typically incorporate additional meteorological variables when available, such as wind speed or relative humidity, to capture processes that temperature alone cannot represent. For example, some approaches adjust the Hargreaves-Samani coefficient based on elevation or seasonal precipitation patterns, acknowledging that the relationship between temperature and evapotranspiration varies with these factors. Other modifications use different formulations for different seasons or climate types, recognizing that the dominant controls on evapotranspiration shift throughout the year. These hybrid approaches demonstrate how empirical models can evolve through incremental improvements while retaining their fundamental advantage of simplicity and data accessibility.

The Stephens-Stewart method, developed in the 1960s for Australian conditions, represents another innovative combination approach that emerged from specific regional needs. Recognizing that many Australian weather stations recorded temperature and humidity but not solar radiation, Stephens and Stewart developed



relationships that could estimate evapotranspiration from these commonly available variables. Their method incorporated the saturation deficit calculated from temperature and humidity measurements, acknowledging that atmospheric moisture demand plays a crucial role in driving evapotranspiration. The approach proved particularly valuable in the Australian context, where vast areas with limited monitoring infrastructure needed practical water management tools. The success of the Stephens-Stewart method in Australia inspired similar regional adaptations in other parts of the world, demonstrating how empirical models can be tailored to specific climatic and data availability contexts.

Regional calibration requirements represent both a strength and limitation of combination methods. While these approaches often perform well in the regions where they were developed, their accuracy can decline significantly when applied elsewhere without adjustment. This has led to the development of region-specific calibration procedures, where locally measured evapotranspiration data are used to adjust model parameters for particular climate zones or vegetation types. The Food and Agriculture Organization has facilitated this process through its extensive work on crop coefficient development, creating standardized procedures for calibrating and validating empirical methods across diverse agricultural systems. This regional calibration approach recognizes that no single empirical relationship can capture the full complexity of evapotranspiration processes worldwide, but that appropriately calibrated empirical models can provide valuable practical tools for water management.

The limitations of empirical models stem primarily from their simplified treatment of the complex physical and biological processes that control evapotranspiration. By reducing these processes to statistical relationships with a few easily measured variables, empirical models inevitably sacrifice accuracy in favor of simplicity and accessibility. These models typically cannot capture the effects of extreme events, unusual weather patterns, or changing vegetation conditions unless specifically calibrated for those situations. They also generally assume steady-state conditions and cannot represent the rapid fluctuations in evapotranspiration that occur throughout the day. Furthermore, most empirical models were developed for specific climate types or vegetation communities and may perform poorly when applied outside their intended range without local calibration. These limitations have become increasingly apparent as researchers attempt to apply these methods in climate change impact assessments, where the statistical relationships on which the models are based may no longer hold true.

Despite these limitations, empirical models continue to find important applications in contemporary water management and research. In developing regions, where comprehensive weather monitoring networks may be lacking, these methods often represent the only practical approach to estimating evapotranspiration for irrigation planning and water resources assessment. For historical climate studies, empirical models allow researchers to reconstruct evapotranspiration patterns back in time before modern measurement techniques were available, providing crucial baseline data for understanding long-term climate variability. In operational water management, the simplicity and computational efficiency of empirical models make them valuable for real-time applications where more complex models would be impractical. Even as sophisticated process-based models and remote sensing products become increasingly available, empirical models continue to serve as valuable tools for data-sparse regions, preliminary assessments, and situations where simplicity outweighs the need for precision.

The enduring relevance of empirical models in an era of increasingly sophisticated alternatives speaks to the fundamental principle that the best model is not always the most complex one, but rather the one that can be practically applied with available data to meet specific management needs. These models, born from necessity and refined through decades of application, continue to play important roles in water management worldwide, from smallholder irrigation planning in developing countries to regional water resources assessments in data-limited regions. Their limitations are well-documented and understood, but their advantages in terms of simplicity, data requirements, and computational efficiency ensure their continued relevance alongside more sophisticated modeling approaches. As we turn our attention to process-based models in the following section, we will see how the empirical relationships developed over decades of observation have informed and continue to complement our more physically-based understanding of evapotranspiration processes.

## 1.6 Process-Based Models

The transition from empirical to process-based models represents a fundamental paradigm shift in evapotranspiration science, moving from statistical relationships to explicit representation of the physical and biological processes that govern water vapor transfer. While empirical models, as discussed in the previous section, provide valuable practical tools through their simplicity and minimal data requirements, they inevitably sacrifice physical realism for accessibility. Process-based models, by contrast, attempt to simulate the actual mechanisms of evapotranspiration based on our understanding of physics, plant physiology, and micrometeorology. This approach, while more demanding in terms of data requirements and computational complexity, offers the potential for greater accuracy, broader applicability across diverse environments, and deeper insight into the controlling factors of evapotranspiration. The development of process-based models has paralleled advances in our theoretical understanding of evapotranspiration processes, creating a virtuous cycle where improved models lead to better predictions, which in turn reveal gaps in our understanding that drive further research.

### 1.6.1 6.1 Penman-Monteith Equation

The Penman-Monteith equation stands as the crown jewel of process-based evapotranspiration modeling, representing the culmination of decades of theoretical development that began with Dalton's evaporation law and reached maturity with Howard Penman's combination approach in 1948. John Monteith's revolutionary contribution in 1965 was to recognize that Penman's physically-based framework could be extended from simple wet surfaces to vegetated surfaces by introducing the concept of surface resistance. This single conceptual breakthrough transformed the Penman equation from a tool for estimating potential evapotranspiration into a comprehensive framework for modeling actual, biologically-controlled evapotranspiration from real ecosystems. The elegance of the Penman-Monteith equation lies in its ability to integrate the two fundamental requirements for evapotranspiration—the supply of energy and the removal of water vapor—while simultaneously accounting for the biological regulation that characterizes transpiration from vegetation.

The theoretical derivation of the Penman-Monteith equation reveals the beautiful synthesis of physical and biological principles that underlies modern evapotranspiration science. At its core, the equation balances the energy available for evapotranspiration (primarily from net radiation) with the atmospheric capacity to absorb water vapor (determined by vapor pressure deficit and aerodynamic resistance). What makes the equation particularly powerful is its explicit treatment of the resistance pathways that control water vapor transfer from inside the leaf to the free atmosphere. The total resistance consists of two components in series: the surface resistance ( $r_s$ ), which represents primarily the stomatal resistance of the vegetation canopy, and the aerodynamic resistance ( $r_a$ ), which represents the efficiency of turbulent transfer through the atmosphere above the canopy. This conceptual framework allows the same fundamental equation to be applied to vastly different surfaces, from open water (where surface resistance approaches zero) to dense forests (where surface resistance may be substantial), simply by adjusting these resistance parameters.

The surface resistance conceptualization introduced by Monteith represents perhaps the most significant advance in evapotranspiration modeling since Penman's original work. This resistance term, measured in seconds per meter, captures the integrated effect of all biological factors that regulate transpiration, including stomatal aperture, leaf area index, canopy structure, and plant water status. When vegetation is well-watered and actively transpiring, surface resistance might be as low as 50-100 s/m for dense agricultural crops. As plants experience water stress or respond to other environmental limitations, this resistance can increase dramatically, sometimes exceeding 1000 s/m, effectively shutting down transpiration to prevent catastrophic water loss. The dynamic nature of surface resistance allows the Penman-Monteith equation to capture the complex ways that vegetation responds to its environment, making it far more than a simple energy balance calculation.

Aerodynamic resistance calculations in the Penman-Monteith framework incorporate the sophisticated understanding of boundary layer meteorology that developed throughout the mid-20th century. Unlike surface resistance, which is determined primarily by biological factors, aerodynamic resistance depends on the physical characteristics of the surface and the atmospheric conditions above it. The calculation typically uses logarithmic wind profile theory to quantify how efficiently turbulence can transport water vapor away from the canopy, with the resistance decreasing as wind speed increases and surface roughness increases. For a short grass surface, aerodynamic resistance might be 50-100 s/m under moderate wind conditions, while for a smooth water surface it could exceed 200 s/m due to the lack of roughness elements to generate turbulence. These calculations, while mathematically complex, incorporate fundamental physical principles that ensure the model behaves realistically across the full range of environmental conditions.

The assumptions and limitations of the Penman-Monteith equation are as important to understand as its theoretical foundations. The equation assumes steady-state conditions, meaning that it works best for time periods of 24 hours or longer when diurnal variations average out. It also assumes that the source of water vapor and heat is at a single height (the "big-leaf" assumption), which may not accurately represent vegetation with complex vertical structure. Furthermore, the equation requires that net radiation not be negative, which limits its application during nighttime periods in many climates. Despite these limitations, the Penman-Monteith equation has proven remarkably robust across diverse environments, from tropical rainforests to arid grasslands, making it the foundation upon which most modern evapotranspiration models are built.

### 1.6.2 6.2 FAO Standardization Efforts

The Food and Agriculture Organization's standardization efforts represent a crucial chapter in the practical application of process-based models, transforming the Penman-Monteith equation from a research tool into a global standard for water management. The challenge that motivated this work was both practical and profound: how could agricultural planners and irrigation engineers worldwide estimate crop water requirements consistently and accurately when they worked with different crops, climates, and levels of technical expertise? The answer emerged through a series of expert consultations and technical papers published between 1977 and 1998, culminating in the FAO Irrigation and Drainage Paper No. 56, which formally established the FAO Penman-Monteith equation as the global standard for calculating reference evapotranspiration.

The FAO Penman-Monteith reference equation represents a carefully calibrated version of the general Penman-Monteith formulation, specifically designed to estimate evapotranspiration from a hypothetical reference surface with standardized characteristics. This reference surface is defined as a hypothetical grass crop with an assumed height of 0.12 meters, a surface resistance of 70 s/m, and an albedo of 0.23. These parameters were not chosen arbitrarily but represent carefully considered values that approximate the behavior of an extensive, well-watered grass surface of uniform height, actively growing and adequately watered. By standardizing both the surface characteristics and the calculation procedures, the FAO created a common reference point that allows for the meaningful comparison of evapotranspiration rates across different locations, seasons, and years. This standardization has been particularly valuable for irrigation scheduling, where crop-specific water requirements can be calculated by multiplying the reference evapotranspiration by appropriate crop coefficients.

The standardized calculation procedures developed by the FAO represent a model of clarity and practicality that has greatly facilitated the global adoption of the Penman-Monteith approach. The FAO guidelines provide detailed step-by-step procedures for calculating all required variables, including explicit formulas for estimating missing meteorological data when complete measurements are unavailable. For example, when solar radiation measurements are not available, the FAO procedure provides methods for estimating it from temperature and sunshine duration. When humidity data are missing, procedures exist for estimating dew point temperature from minimum temperature. These practical accommodations acknowledge the reality that many agricultural locations, particularly in developing countries, lack comprehensive weather monitoring infrastructure. By providing scientifically sound methods for working with incomplete data, the FAO has made sophisticated evapotranspiration modeling accessible to users worldwide.

Weather data requirements and quality checks represent another crucial aspect of the FAO standardization effort. The reference equation requires measurements of maximum and minimum temperature, maximum and minimum relative humidity (or dew point temperature), wind speed at 2 meters height, and solar radiation. Recognizing that data quality can vary dramatically between weather stations, the FAO developed comprehensive quality control procedures that help identify suspicious values, fill small data gaps, and assess the reliability of the input data. These procedures include checks for reasonable ranges of values, internal consistency between related variables, and temporal continuity. The emphasis on data quality reflects the FAO's understanding that even the most sophisticated model will produce unreliable results if fed with poor

quality data—a lesson that applies equally to all process-based modeling approaches.

The global adoption and implementation of the FAO Penman-Monteith standard represents one of the most successful examples of scientific standardization in agricultural practice. Within a decade of its formal introduction in 1998, the method had been incorporated into irrigation scheduling software, crop models, and water management guidelines worldwide. Agricultural extension services from California to China began training farmers and irrigation managers in its use, while international development projects incorporated it into water resource assessments across Africa, Asia, and Latin America. The method has also been implemented in numerous automated weather station networks, providing real-time estimates of reference evapotranspiration that can be accessed via web services and mobile applications. This widespread adoption has created a common language for agricultural water management that transcends national boundaries and cultural differences, facilitating international cooperation on water-related challenges.

### 1.6.3 6.3 Resistance Network Approaches

The development of resistance network approaches represents a natural extension of the Penman-Monteith framework, addressing the limitations of the “big-leaf” assumption through more sophisticated representations of vegetation structure and environmental heterogeneity. While the single-layer Penman-Monteith equation treats the entire canopy as a single uniform surface, resistance network models recognize that real vegetation canopies have complex vertical structure with significant variations in environmental conditions throughout their depth. These models conceptualize water vapor transfer as a network of resistances arranged in series and parallel, each representing different pathways and controlling factors. This more detailed representation allows for the simulation of processes that single-layer models cannot capture, such as the differential transpiration of sunlit and shaded leaves, the contribution of understory vegetation to total evapotranspiration, and the vertical profiles of temperature and humidity within dense canopies.

Multi-layer resistance models represent the most sophisticated implementations of the resistance network approach, dividing the canopy into multiple layers and calculating energy balance and water vapor transfer separately for each layer. These models typically require detailed information about canopy structure, including leaf area distribution by height, leaf angle distribution, and optical properties. For each layer, the model calculates the absorbed radiation, which decreases exponentially with depth according to the Beer-Lambert law, and then determines the transpiration rate based on the energy available and the resistance to water vapor transfer. The contributions from all layers are then integrated to determine the total canopy transpiration. While computationally intensive, these models have provided valuable insights into canopy functioning that would be impossible to obtain from single-layer approaches. For example, multi-layer models have revealed that in dense forests, the majority of transpiration often comes from the upper third of the canopy where radiation is most available, while shaded leaves in the lower canopy contribute relatively little despite representing a substantial portion of the total leaf area.

Canopy resistance parameterization in resistance network models has evolved significantly from the simple constant values used in early implementations. Modern approaches recognize that canopy resistance emerges from the complex interaction of numerous environmental factors, each affecting stomatal aperture in different

ways. Light intensity typically follows a saturating response, with stomata opening rapidly at low light levels and gradually reaching a maximum at higher intensities. Vapor pressure deficit often shows an optimum response, with stomata opening at moderate deficits but closing at very high deficits to prevent excessive water loss. Temperature responses are typically bell-shaped, with reduced stomatal conductance at both low and high temperatures. Soil water availability introduces another layer of complexity, with different species showing varying strategies for maintaining transpiration under drought conditions. By combining these individual response functions, resistance network models can simulate the dynamic behavior of canopy resistance across the full range of environmental conditions experienced in natural ecosystems.

Soil resistance integration represents another important advancement in resistance network modeling, acknowledging that water must move through the soil before it can even reach plant roots. Early models often assumed unlimited soil water availability, but modern implementations recognize that soil resistance can become significant as soils dry, particularly in the rhizosphere immediately surrounding roots where water extraction can create local depletion zones. The calculation of soil resistance typically requires knowledge of soil hydraulic properties, root distribution, and the spatial pattern of water uptake. Some sophisticated models even simulate the feedback between transpiration and soil water potential, where increased transpiration leads to drier soils, which in turn increases soil resistance and limits further transpiration. This coupling between atmospheric demand and soil supply represents one of the most important advances in our understanding of ecosystem water balance, helping to explain why some forests maintain relatively constant transpiration while others show strong declines during drought periods.

The comparison between big-leaf and multi-layer models reveals important trade-offs between complexity and practicality that continue to shape the development of evapotranspiration models. Big-leaf models, with their single-layer representation, require minimal data about canopy structure and can be calibrated relatively easily, making them attractive for operational applications. Their primary limitation is the inability to capture within-canopy variability, which can be significant in tall, heterogeneous vegetation. Multi-layer models, while more theoretically sound, require detailed canopy structure data that are often unavailable and involve substantial computational demands. The choice between approaches often depends on the application: big-leaf models may be sufficient for agricultural fields with relatively uniform canopy structure, while multi-layer models may be necessary for old-growth forests with complex vertical structure. Some researchers have developed intermediate approaches with two or three layers that attempt to capture the most important aspects of canopy heterogeneity while maintaining reasonable data requirements and computational efficiency.

#### **1.6.4 6.4 Stomatal Conductance Modeling**

Stomatal conductance modeling represents perhaps the most biologically detailed aspect of process-based evapotranspiration models, focusing on the microscopic pores that regulate the exchange of water vapor and carbon dioxide between leaves and the atmosphere. The importance of stomatal modeling stems from the recognition that stomata serve as the primary control point for transpiration in most vegetation, adjusting their aperture in response to a complex array of environmental signals. These remarkable structures, typically numbering in the thousands per square centimeter of leaf surface, can change their opening area by factors



of ten or more within minutes, allowing plants to balance the conflicting needs for carbon dioxide uptake and water conservation. Understanding and accurately modeling this dynamic regulation is essential for predicting how vegetation will respond to changing environmental conditions, from diurnal variations in light and humidity to long-term shifts in climate patterns.

Jarvis-type stomatal models, developed by Paul Jarvis in 1976, represent the pioneering approach to mechanistic stomatal conductance modeling. Jarvis recognized that stomatal aperture responds to multiple environmental factors simultaneously, and he proposed that the combined effect could be represented by multiplying individual response functions for each factor. His framework included responses to photosynthetic photon flux density (light), vapor pressure deficit, leaf temperature, and leaf water potential. Each response function was represented by a dimensionless factor ranging from 0 (completely closed stomata) to 1 (maximum opening), with the actual conductance calculated as the product of these factors multiplied by a maximum conductance parameter. This modular approach proved highly influential and formed the basis for numerous subsequent models. The elegance of the Jarvis framework lies in its flexibility: individual response functions can be easily modified or new factors added as understanding advances, while the basic multiplicative structure remains intact. However, the approach also has limitations, particularly its empirical nature and the assumption that different environmental factors act independently, which may not always be the case.

The Ball-Berry conductance formulation, published in 1987, marked a significant theoretical advance by linking stomatal conductance directly to photosynthesis. This relationship emerged from the recognition that stomata do not respond to environmental factors in isolation but rather regulate their opening to maintain an optimal balance between carbon dioxide intake and water loss. Ball, Woodrow, and Berry proposed that stomatal conductance is proportional to photosynthesis rate, relative humidity, and inversely proportional to carbon dioxide concentration at the leaf surface. This formulation has a strong physiological basis: as photosynthesis increases with higher light intensity, stomata open to supply the necessary carbon dioxide; as humidity decreases, stomata close to prevent excessive water loss; as atmospheric carbon dioxide increases, stomata can partially close while maintaining the same carbon uptake. The Ball-Berry model has been widely incorporated into vegetation models and ecosystem models, providing a mechanistic link between the carbon and water cycles that is essential for understanding ecosystem responses to rising atmospheric carbon dioxide levels.

Medlyn model advancements, published in 2011 by Belinda Medlyn and colleagues, represent the latest evolution in stomatal conductance modeling, building on the Ball-Berry framework while incorporating more recent understanding of stomatal function. The Medlyn model emerged from a theoretical optimization approach that assumes stomata regulate to maximize carbon gain for a given water loss, leading to a different mathematical formulation than the Ball-Berry model. The key innovation is the explicit inclusion of a parameter

## 1.7 Remote Sensing Applications

While process-based models have revolutionized our theoretical understanding of evapotranspiration, their practical application has always been constrained by a fundamental limitation: the need for detailed input

data that can only be obtained from point measurements or sparse weather stations. A single lysimeter or eddy covariance tower, no matter how sophisticated, can only provide information for the immediate footprint it represents, leaving vast areas between measurement sites uncharacterized. This spatial sampling limitation became increasingly apparent as researchers sought to understand evapotranspiration patterns across landscapes, regions, and ultimately the entire globe. The solution to this challenge emerged not from the ground but from space, as advances in satellite remote sensing beginning in the 1970s opened new possibilities for observing Earth's surface from above. The development of remote sensing applications for evapotranspiration represents one of the most significant technological breakthroughs in hydrological science, transforming our ability to monitor water use across scales from individual fields to entire continents.

### 1.7.1 7.1 Satellite-Based Estimation Principles

The fundamental premise of satellite-based evapotranspiration estimation rests on the observation that energy balance at Earth's surface creates detectable signatures that can be measured from space. When evapotranspiration is high, a substantial portion of available energy goes into the latent heat flux, resulting in relatively cool surface temperatures. Conversely, when evapotranspiration is limited by water scarcity, the same energy input primarily heats the surface, creating higher temperatures that can be detected by thermal infrared sensors. This relationship between surface temperature and evapotranspiration provides the physical basis for most satellite-based approaches, allowing us to infer water use patterns from the thermal behavior of the landscape. The elegance of this approach lies in its ability to leverage a single satellite measurement (surface temperature) to estimate a complex process that depends on numerous interacting factors including radiation balance, atmospheric conditions, vegetation characteristics, and soil moisture availability.

The surface temperature-vegetation index triangle method represents one of the most intuitive and widely used approaches for satellite-based evapotranspiration estimation. This technique, first systematically described by Moran and colleagues in the 1990s, exploits the characteristic triangular pattern that emerges when plotting surface temperature against vegetation indices (such as NDVI) for pixels within a relatively homogeneous area. The triangle's vertices represent three extreme conditions: bare, dry soil (high temperature, low vegetation); dense, well-watered vegetation (low temperature, high vegetation); and water bodies (very low temperature, variable vegetation index). By understanding where individual pixels fall within this triangle space, researchers can estimate relative evapotranspiration rates across the landscape. This approach has proven particularly valuable for agricultural monitoring, where it can identify water-stressed fields that may require irrigation intervention. The method's simplicity and minimal data requirements have made it popular for operational applications in regions with limited access to sophisticated processing capabilities.

The launch of NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) sensors in 1999 aboard the Terra and Aqua satellites marked a watershed moment for satellite-based evapotranspiration monitoring. MODIS provided, for the first time, global coverage with daily revisit time and spectral bands specifically designed for terrestrial monitoring. Building on this capability, researchers at the University of Montana developed the MODIS Global Evapotranspiration Project (MOD16), which has produced continuous global evapotranspiration datasets since 2000. The MOD16 algorithm combines satellite observations of vegetation



properties with meteorological reanalysis data in a modified Penman-Monteith framework, producing 8-day, 500-meter resolution evapotranspiration estimates worldwide. This dataset has transformed our understanding of global water cycling, revealing patterns such as the “flying rivers” of moisture that flow from the Amazon to other parts of South America, and documenting trends in evapotranspiration that may be related to climate change and land use change.

Geostationary satellites have emerged as powerful complementary tools for evapotranspiration monitoring, offering temporal resolution that polar-orbiting satellites cannot match. While satellites like MODIS provide global coverage with daily revisit time, geostationary satellites such as GOES (United States), Meteosat (Europe), and Himawari (Japan) observe the same location every 10-15 minutes. This high temporal resolution allows for the observation of diurnal evapotranspiration patterns and the detection of rapid changes in water use that might be missed by daily observations. The GOES-R series, launched beginning in 2016, includes advanced thermal infrared sensors with spatial resolution as fine as 2 kilometers and temporal resolution as frequent as 5 minutes, enabling near-real-time monitoring of evapotranspiration for applications such as drought early warning and irrigation scheduling. The combination of polar-orbiting and geostationary observations provides both comprehensive spatial coverage and detailed temporal dynamics, creating a more complete picture of evapotranspiration processes than either system could provide alone.

The physical principles underlying satellite-based evapotranspiration estimation continue to evolve as researchers develop more sophisticated algorithms that can extract additional information from multispectral observations. Modern approaches often combine multiple satellite-derived variables—including surface temperature, vegetation indices, albedo, and land surface emissivity—in complex energy balance models that account for the heterogeneous nature of real landscapes. These advances have been accompanied by improvements in atmospheric correction procedures that account for the effects of water vapor, aerosols, and clouds on satellite observations, ensuring that the surface signals truly represent ground conditions rather than atmospheric interference. The result has been a steady improvement in the accuracy and reliability of satellite-derived evapotranspiration estimates, with validation studies typically showing correlations of 0.8-0.9 with ground measurements from flux towers when appropriate scaling and validation procedures are applied.

### **1.7.2 7.2 Thermal Infrared Techniques**

Thermal infrared remote sensing represents the cornerstone of most satellite-based evapotranspiration approaches, leveraging the fundamental relationship between surface energy balance and temperature. The technical challenges of retrieving accurate surface temperatures from space are substantial and have driven decades of research in atmospheric physics and remote sensing methodology. Raw thermal infrared measurements acquired by satellite sensors do not directly represent surface temperatures but rather represent the radiation emitted by the surface after it has been partially absorbed and re-emitted by the atmosphere along the path to the sensor. This atmospheric effect can change the apparent temperature by several degrees Celsius, potentially creating errors in evapotranspiration estimates that exceed 30% if not properly corrected. The development of sophisticated atmospheric correction methods, including split-window tech-

niques that use multiple thermal bands to estimate and remove atmospheric effects, has been essential for making thermal infrared remote sensing viable for evapotranspiration monitoring.

Surface temperature retrieval challenges become particularly acute in heterogeneous landscapes where different surface materials emit thermal radiation with different efficiencies. This property, known as emissivity, varies from near 1.0 for water bodies to 0.85-0.95 for most natural surfaces, creating variations in apparent temperature that have nothing to do with actual surface conditions but rather with how efficiently different materials emit thermal radiation. Early satellite systems often assumed a constant emissivity for all land surfaces, introducing systematic errors that were particularly problematic in arid regions with exposed rock and soil. Modern approaches use temperature-emissivity separation algorithms that simultaneously retrieve both surface temperature and emissivity from multiple thermal infrared measurements, dramatically improving accuracy. These technical advances have been crucial for applications such as monitoring evapotranspiration from sparsely vegetated rangelands, where small differences in surface temperature can indicate important variations in water availability and ecosystem stress.

The Temperature-Vegetation Dryness Index (TVDI) represents an innovative application of thermal infrared remote sensing that has proven particularly valuable for drought monitoring and agricultural water management. Developed by Sandholt and colleagues in 2002, TVDI uses the relationship between surface temperature and vegetation indices to estimate relative soil moisture availability across landscapes. The method works by establishing the theoretical boundaries between wet and dry extremes within the temperature-vegetation index space for each image, then calculating where individual pixels fall between these extremes. This approach has the advantage of not requiring absolute temperature calibration, making it relatively robust to atmospheric and emissivity effects. TVDI has been widely implemented in operational drought monitoring systems, including the U.S. Drought Monitor, where it provides valuable information about vegetation stress that complements traditional precipitation-based drought indicators. The method's ability to detect emerging drought conditions before they become apparent in vegetation growth patterns makes it particularly valuable for early warning applications.

The Surface Energy Balance Algorithm for Land (SEBAL), developed by Bastiaanssen and colleagues in the 1990s, represents one of the most sophisticated and widely applied thermal infrared approaches to evapotranspiration estimation. SEBAL uses a combination of satellite-derived surface temperature, vegetation indices, and albedo along with limited meteorological data to solve the surface energy balance equation for each pixel independently. The algorithm's innovation lies in its use of "anchor pixels"—extreme hot/dry and cold/wet pixels within each image—to internally calibrate the energy balance without requiring extensive ground measurements. This internal calibration makes SEBAL remarkably robust and transferable across different environments, from irrigated agricultural fields to natural ecosystems. The method has been applied successfully in more than 30 countries, providing crucial information for water management in data-sparse regions. Perhaps its most notable success has been in the Indus Basin of Pakistan, where SEBAL-based estimates of evapotranspiration and water productivity have helped identify opportunities to save water through improved irrigation management.

The Mapping Evapotranspiration at High Resolution with Internalized Calibration (METRIC) algorithm, de-

veloped by Allen and colleagues as an adaptation of SEBAL for U.S. conditions, represents another significant advancement in thermal infrared evapotranspiration mapping. METRIC builds on the SEBAL framework but incorporates several improvements that make it particularly suitable for agricultural applications in temperate climates. These include the use of reference evapotranspiration from weather stations to anchor the energy balance calculations, improved procedures for identifying anchor pixels, and methods for interpolating evapotranspiration between satellite overpass dates. METRIC has been widely adopted by water managers in the western United States, where it provides crucial information for water rights administration, irrigation planning, and drought response. The method's ability to map evapotranspiration at field-scale resolution (30 meters with Landsat data) has made it particularly valuable for applications such as identifying water losses from irrigation canals, evaluating the effectiveness of water conservation measures, and settling water disputes between competing users.

### 1.7.3 7.3 Vegetation Indices Integration

Vegetation indices represent powerful tools for evapotranspiration estimation because they provide information about vegetation characteristics that fundamentally control transpiration rates. The Normalized Difference Vegetation Index (NDVI), calculated from the contrast between near-infrared and red reflectance, has been the workhorse vegetation index for evapotranspiration studies since the early days of satellite remote sensing. NDVI correlates strongly with several vegetation properties relevant to transpiration, including leaf area index, fractional vegetation cover, and photosynthetic capacity. Higher NDVI values typically indicate denser, healthier vegetation with greater transpiration potential, while lower values suggest sparse or stressed vegetation with reduced water use. This relationship has been exploited in numerous evapotranspiration algorithms that use NDVI to estimate parameters such as surface resistance, crop coefficients, and vegetation fraction. The simplicity of NDVI (requiring only two spectral bands) and its long historical record (available from early satellite sensors like Landsat MSS launched in 1972) have made it invaluable for studying long-term trends in evapotranspiration related to vegetation changes, drought impacts, and land use transformations.

The Enhanced Vegetation Index (EVI) was developed to address some limitations of NDVI, particularly its sensitivity to atmospheric conditions and its tendency to saturate in dense vegetation. EVI incorporates the blue band to correct for atmospheric influences and includes a feedback term to reduce sensitivity to canopy background variations, making it more responsive to structural changes in dense vegetation. For evapotranspiration applications, EVI often provides better correlation with transpiration rates in forests and other high-biomass ecosystems where NDVI may saturate. The MODIS sensor provides both NDVI and EVI products at 250-meter resolution with 16-day compositing periods, allowing researchers to choose the index that best suits their particular ecosystem and application. Studies comparing the two indices have shown that while NDVI may be superior for sparse vegetation and early growth stages, EVI often performs better for mature forests and other dense canopies where subtle variations in vegetation condition can indicate important changes in water use patterns.

Leaf area index (LAI) represents a more physically-based vegetation parameter that has strong theoretical

connections to evapotranspiration through the Penman-Monteith equation. LAI quantifies the total one-sided area of leaves per unit ground surface area, directly influencing both the interception of radiation (energy availability) and the total stomatal surface area (water vapor transfer capacity). Satellite-based LAI estimation typically involves empirical relationships with vegetation indices or more sophisticated radiative transfer models that simulate how radiation interacts with vegetation canopies. Modern LAI products, such as those from MODIS and the Copernicus Global Land Service, provide global coverage at 500-meter to 1-kilometer resolution with 8-day to 10-day temporal resolution. These datasets have been invaluable for ecosystem-scale evapotranspiration modeling, allowing researchers to capture the phenological dynamics of vegetation growth and senescence that drive seasonal patterns in transpiration. The integration of LAI into evapotranspiration models has significantly improved our ability to predict water use across diverse ecosystems, from grasslands with LAI values around 1 to tropical rainforests with LAI exceeding 6.

Fractional vegetation cover estimation represents another important application of vegetation indices for evapotranspiration monitoring. This parameter quantifies the proportion of ground surface covered by green vegetation, distinguishing between areas where transpiration occurs and bare soil where only evaporation takes place. Fractional cover can be estimated from vegetation indices using linear mixture models that assume each pixel's reflectance is a combination of vegetated and non-vegetated components. For evapotranspiration applications, fractional cover is crucial because it allows for the separate estimation of transpiration and soil evaporation, which respond differently to environmental conditions. In agricultural landscapes, fractional cover estimation from satellites like Sentinel-2 (which provides 10-meter resolution) can distinguish between different crop types, growth stages, and even within-field variability, enabling precision irrigation applications that apply water only where needed. The ability to monitor changes in fractional cover throughout the growing season also provides valuable information for understanding how vegetation development influences water use patterns in both natural and managed ecosystems.

Phenological cycle monitoring using satellite vegetation indices has revealed fascinating insights into the relationship between vegetation dynamics and evapotranspiration patterns. The timing of green-up, peak growth, and senescence varies systematically with climate, elevation, and vegetation type, creating characteristic patterns in seasonal evapotranspiration cycles. In temperate regions, satellite observations have documented trends toward earlier spring green-up and later autumn senescence in response to warming temperatures, potentially extending the growing season and increasing annual evapotranspiration. In tropical regions, subtle variations in phenology related to dry season length and intensity have been linked to shifts in ecosystem water use that may influence rainfall patterns. These phenological observations have become particularly valuable for understanding how ecosystems respond to climate variability and for predicting how evapotranspiration patterns might shift under future climate scenarios. The continuous, multi-decadal record of vegetation indices from satellites like AVHRR (since 1981), MODIS (since 2000), and Sentinel-2 (since 2015) provides an unparalleled resource for studying these long-term changes in vegetation-water relationships.

Stress detection applications represent one of the most promising uses of vegetation indices for evapotranspiration monitoring, particularly in agricultural contexts. When plants experience water stress, they often close their stomata to conserve water, leading to reduced transpiration and sometimes visible changes in leaf

optical properties. These changes can be detected through vegetation indices before they become apparent to the human eye, providing early warning of irrigation needs or drought impacts. More sophisticated approaches use combinations of vegetation indices and thermal measurements to identify stress conditions, as water-stressed vegetation typically shows reduced NDVI or EVI coupled with higher surface temperatures compared to well-watered vegetation. The integration of these multiple indicators has been implemented in various precision agriculture systems, allowing farmers to apply water variably across fields based on actual crop needs rather than uniform application. These applications demonstrate how satellite observations can translate into practical water savings while maintaining or even improving crop yields, representing a crucial step toward more sustainable agricultural water management.

#### **1.7.4 7.4 Multi-Sensor Data Fusion**

The integration of data from multiple satellite sensors has emerged as a powerful strategy for overcoming the limitations of individual observation systems and creating more comprehensive evapotranspiration products. Each remote sensing platform offers unique advantages in terms of spatial resolution, temporal coverage, spectral capabilities, and all-weather observation capacity, but no single system can provide optimal conditions for all applications. Multi-sensor data fusion attempts to combine the strengths of different systems while mitigating their weaknesses, creating composite products that offer superior performance

### **1.8 Climate Change Impacts**

While multi-sensor data fusion represents a remarkable technical achievement in our ability to monitor evapotranspiration across space and time, it simultaneously provides the observational foundation needed to address one of the most pressing questions in contemporary hydrology: how will climate change alter these fundamental patterns of water exchange between land and atmosphere? The sophisticated monitoring systems we've developed are not merely academic exercises; they are essential tools for detecting, attributing, and predicting the responses of evapotranspiration to a rapidly changing climate. As global temperatures continue to rise and precipitation patterns shift, understanding these responses becomes increasingly critical for water resource management, agricultural planning, and ecosystem conservation. The complex interplay between climate change and evapotranspiration represents one of the most significant uncertainties in Earth system science, with profound implications for virtually every aspect of human society and natural ecosystems.

#### **1.8.1 8.1 Temperature Effects and Trends**

The relationship between rising global temperatures and evapotranspiration responses follows a complex, non-linear pattern that challenges simplistic assumptions about warming inevitably leading to increased water loss. Fundamental physics dictates that warmer air can hold more water vapor, with the saturation vapor pressure increasing by approximately 7% for each degree Celsius of temperature rise according to

the Clausius-Clapeyron relationship. This thermodynamic effect alone would suggest substantial increases in atmospheric evaporative demand under climate change. However, actual evapotranspiration responses are moderated by numerous biological and physical constraints, including water availability, vegetation responses, and the interplay between energy and water limitations. The result is a mosaic of responses across different ecosystems and climate zones, with some regions showing increased evapotranspiration while others experience declines despite warming temperatures.

Non-linear temperature-ET relationships emerge clearly when examining long-term observational records from flux tower networks worldwide. In water-limited ecosystems, rising temperatures initially increase evapotranspiration rates up to a certain threshold, beyond which water availability becomes the limiting factor and further warming leads to reduced water loss. This pattern has been documented across numerous semi-arid regions, from the southwestern United States to the Sahel in Africa, where decades of warming have sometimes coincided with declining evapotranspiration due to soil moisture depletion. Conversely, in energy-limited systems like high-latitude forests and tropical cloud forests, warming has generally led to increased evapotranspiration as higher temperatures reduce constraints on energy availability. These divergent responses highlight the importance of understanding whether evapotranspiration in a particular ecosystem is primarily controlled by water supply or energy availability—a distinction that becomes increasingly crucial under climate change.

Extreme heat wave impacts on transpiration reveal another layer of complexity in temperature-ET relationships. The unprecedented 2021 Pacific Northwest heat dome, which saw temperatures soar to 49.6°C in British Columbia, provided a natural experiment in how vegetation responds to extreme temperature stress. Eddy covariance measurements during this event documented initial increases in transpiration as temperatures rose, followed by abrupt declines as plants closed their stomata to prevent catastrophic water loss. In some cases, this stomatal closure was so severe that it led to hydraulic failure and widespread vegetation mortality, permanently reducing the transpiration capacity of affected forests. Similar patterns have been observed during European heat waves, where extreme temperatures have triggered both temporary reductions in transpiration and long-term changes in forest composition toward more drought-tolerant species with potentially different water use characteristics.

Urban heat island amplification adds another dimension to temperature effects on evapotranspiration, with cities typically experiencing temperatures 2-5°C higher than surrounding rural areas. This temperature differential creates distinct evapotranspiration patterns within urban environments, where impervious surfaces limit water availability while elevated temperatures increase atmospheric demand. Research using thermal infrared remote sensing has revealed that urban parks and green spaces can maintain substantially higher evapotranspiration rates than surrounding built-up areas, creating cool islands that can reduce local temperatures by 1-2°C. However, this cooling effect depends on adequate water availability, and during drought periods, urban vegetation may experience water stress that reduces its evaporative cooling capacity. The expansion of urban areas worldwide, combined with increasing temperatures, creates complex feedbacks between urban development, local climate, and evapotranspiration that must be considered in urban planning and water management.



### 1.8.2 8.2 Changing Precipitation Patterns

Altered rainfall distribution effects represent perhaps the most direct way that climate change influences evapotranspiration, as precipitation provides the fundamental water source for both soil evaporation and plant transpiration. Climate models consistently project increased precipitation variability, with more intense rainfall events separated by longer dry periods in many regions. This shift toward more extreme precipitation patterns creates challenging conditions for vegetation and soil moisture dynamics. Intense rainfall events often exceed infiltration capacity, leading to runoff rather than soil moisture recharge, while extended dry periods between events increase evaporative demand and deplete soil water reserves. The net effect in many regions is a reduction in the fraction of precipitation that is ultimately returned to the atmosphere through evapotranspiration, potentially altering regional water balances and atmospheric moisture recycling.

Drought frequency and duration impacts have become increasingly apparent in observational records across multiple continents. The California megadrought, which persisted from 2011 to 2017 with brief reprieves, provides a compelling case study of how changing precipitation patterns affect evapotranspiration. Analysis of satellite data during this period revealed a 15-20% reduction in evapotranspiration across the state's agricultural regions, with particularly severe declines in the Central Valley where irrigation water was curtailed. Simultaneously, measurements from the FLUXNET network showed that native ecosystems responded differently: some chaparral and oak woodland communities maintained relatively stable evapotranspiration by accessing deep soil moisture, while grasslands showed rapid declines as surface soils dried. These differential responses highlight how vegetation type and rooting depth mediate the impacts of precipitation changes on evapotranspiration patterns.

Intense precipitation events and soil moisture dynamics interact in complex ways that influence evapotranspiration at multiple time scales. While extreme rainfall can temporarily increase soil moisture and boost evapotranspiration rates, the accompanying cloud cover often reduces solar radiation, limiting energy availability for evaporation. Furthermore, the high intensity of these events means that a substantial portion of rainfall may runoff rather than infiltrate, particularly on compacted agricultural soils or urban surfaces. Research using high-resolution temporal data from soil moisture sensor networks has revealed that the legacy effects of extreme precipitation events can persist for weeks, with enhanced evapotranspiration following the event gradually declining as soil moisture returns to baseline levels. These temporal dynamics are often missed by satellite observations with coarse temporal resolution, highlighting the importance of ground-based measurements for understanding precipitation-ET relationships.

Seasonal shift consequences become particularly apparent when examining phenological changes in vegetation growth patterns. In many temperate regions, earlier springs and later falls have extended the growing season, potentially increasing annual evapotranspiration. However, these phenological shifts may create mismatches between water availability and vegetation demand. For example, earlier snowmelt in mountainous regions can advance the onset of transpiration, potentially depleting soil moisture before the peak of summer drought. Similarly, delayed autumn senescence may extend transpiration into periods when precipitation has typically decreased, creating water stress conditions that affect both vegetation health and subsequent year's growth. These phenological mismatches have been documented across diverse ecosystems, from European

forests where spring advancement has created moisture deficits during early summer, to African savannas where delayed rains have disrupted the synchrony between grass growth and herbivore migrations.

### 1.8.3 8.3 CO<sub>2</sub> Fertilization Effects

Stomatal conductance reduction under elevated CO<sub>2</sub> represents one of the most well-documented plant physiological responses to atmospheric change, with profound implications for evapotranspiration. As atmospheric CO<sub>2</sub> concentrations have risen from pre-industrial levels of approximately 280 ppm to current levels exceeding 420 ppm, plants have responded by partially closing their stomata—the microscopic pores that regulate gas exchange between leaves and the atmosphere. This response occurs because higher CO<sub>2</sub> concentrations allow plants to maintain photosynthesis while reducing stomatal aperture, simultaneously decreasing water loss. Free-Air CO<sub>2</sub> Enrichment (FACE) experiments, which expose vegetation to elevated CO<sub>2</sub> concentrations in natural settings, have consistently documented this effect across numerous species and ecosystems. In the Duke Forest FACE experiment, for example, elevated CO<sub>2</sub> reduced stomatal conductance by approximately 20%, leading to comparable reductions in transpiration rates.

Water use efficiency improvements represent the direct consequence of stomatal responses to elevated CO<sub>2</sub>, with plants typically achieving more photosynthesis per unit of water transpired under higher CO<sub>2</sub> conditions. This increased water use efficiency has been observed across scales from individual leaves to entire ecosystems, with implications for both plant productivity and hydrological cycling. In agricultural systems, CO<sub>2</sub> fertilization effects have contributed to yield increases even as transpiration rates have declined, creating what researchers term “more crop per drop.” However, the magnitude of these effects varies substantially among species, with C<sub>4</sub> plants like corn showing smaller responses than C<sub>3</sub> plants like wheat and rice. In natural ecosystems, increased water use efficiency may enhance drought resilience by allowing plants to maintain physiological processes during water-limited periods, potentially altering competitive relationships and community composition.

Compensating effects of increased leaf area add complexity to predictions about how elevated CO<sub>2</sub> will influence evapotranspiration at ecosystem scales. While individual leaves may become more water-efficient, plants often respond to elevated CO<sub>2</sub> by producing more leaf area, increasing the total surface area for transpiration. In some FACE experiments, these compensatory effects have largely offset the water savings from reduced stomatal conductance, resulting in minimal changes in whole-plant or ecosystem-level transpiration. The Amazon FACE experiment, which began in 2015, is currently investigating these interactions in the world’s largest tropical forest, with preliminary results suggesting complex responses that vary among canopy layers and species. Understanding whether increased water use efficiency at leaf level translates to water savings at ecosystem scale represents one of the critical uncertainties in predicting evapotranspiration responses to rising CO<sub>2</sub>.

Long-term ecosystem responses to elevated CO<sub>2</sub> may differ substantially from short-term experimental results due to acclimation processes and nutrient limitations. As plants continue to experience elevated CO<sub>2</sub> over decades to centuries, various compensatory mechanisms may reduce the initial physiological responses. Nitrogen limitation in particular may constrain the ability of plants to increase leaf area or photosynthetic



capacity under elevated CO<sub>2</sub>, potentially limiting the compensatory effects that maintain transpiration rates. Furthermore, evolutionary processes operating over generations may select for genotypes with different stomatal regulation strategies, potentially altering long-term trajectories of evapotranspiration responses. These long-term considerations highlight the challenges of extrapolating from relatively short-term experiments to century-scale climate responses, emphasizing the need for both continued experimental work and improved modeling of plant physiological responses to changing CO<sub>2</sub>.

#### **1.8.4 8.4 Regional Variations and Hotspots**

Mediterranean climate zone vulnerabilities have become increasingly apparent as climate change progresses, with regions like Southern Europe, California, Chile, South Africa, and southwestern Australia experiencing some of the most pronounced changes in evapotranspiration patterns. These regions share a characteristic climate of wet winters and dry summers, making them particularly sensitive to changes in precipitation timing and temperature. Research using long-term flux tower records has documented declining evapotranspiration trends in many Mediterranean ecosystems as summer droughts intensify and extend further into spring and autumn. In California's Sierra Nevada mountains, for example, earlier snowmelt and reduced summer precipitation have led to a 10-15% decline in forest evapotranspiration over the past two decades, with associated increases in tree mortality and wildfire risk. These changes have profound implications for water resources, as reduced evapotranspiration in mountainous watersheds can decrease atmospheric moisture recycling that contributes to precipitation in adjacent regions.

Tropical rainforest responses to climate change remain one of the largest uncertainties in evapotranspiration science, with potential feedbacks that could significantly influence global climate patterns. The Amazon rainforest, in particular, functions as a massive "flying river," recycling approximately 50% of rainfall through evapotranspiration and transporting this moisture to agricultural regions in southern Brazil and neighboring countries. Climate model projections suggest that continued deforestation and climate change could push portions of the Amazon toward a tipping point where evapotranspiration declines sufficiently to alter regional rainfall patterns, potentially leading to forest dieback and conversion to savanna. However, observational evidence remains mixed, with some studies showing resilience in evapotranspiration rates despite warming temperatures, possibly due to CO<sub>2</sub> fertilization effects and deep-rooted vegetation accessing soil moisture reserves. The AttaScale project, which combines aircraft measurements with satellite observations, is currently providing unprecedented detail on how evapotranspiration varies across the Amazon basin and how it responds to climate variability.

High latitude warming impacts are creating some of the most dramatic changes in evapotranspiration patterns globally, as Arctic and boreal regions warm at rates 2-4 times the global average. Permafrost thaw is fundamentally altering hydrological pathways in these regions, creating new surface water connections and increasing the availability of liquid water for evapotranspiration during the extended growing season. Research in Siberia and Alaska has documented increases in evapotranspiration rates of 20-30% over the past three decades, driven primarily by warming temperatures and lengthening growing seasons rather than precipitation changes. These increases in evapotranspiration have complex effects on regional water balances,

potentially reducing river runoff despite increased precipitation in some areas. Furthermore, as permafrost thaw releases previously frozen organic matter, microbial decomposition increases CO<sub>2</sub> and methane emissions, creating feedbacks that may further accelerate warming and evapotranspiration changes.

Semi-arid region amplification represents another hotspot of climate change impacts, where small changes in temperature and precipitation can create disproportionately large changes in evapotranspiration patterns. The Sahel region of Africa, for example, has experienced complex and sometimes counterintuitive changes in evapotranspiration as rainfall patterns have shifted. While some areas have seen slight increases in precipitation, rising temperatures have increased atmospheric evaporative demand, potentially offsetting water availability gains. Satellite observations have revealed a “greening” trend in parts of the Sahel since the 1980s, with increased vegetation cover potentially enhancing evapotranspiration. However, this greening may be limited by nutrient availability and could reverse if climate change intensifies drought conditions. Similar complexities emerge in other semi-arid regions, from the Australian outback to the American Southwest, where evapotranspiration responses to climate change reflect the interplay between temperature, precipitation, vegetation dynamics, and human water use.

### 1.8.5 8.5 Feedback Mechanisms

Cloud formation and precipitation feedbacks create some of the most complex and potentially consequential interactions between evapotranspiration and climate. Evapotranspiration from land surfaces provides a significant source of atmospheric moisture that can influence cloud formation and precipitation patterns, particularly in continental interiors. Research using moisture tracking models has revealed that in some regions, more than half of annual rainfall originates from evapotranspiration within the same watershed—a process known as precipitation recycling. As climate change alters evapotranspiration patterns, these recycling rates may change, potentially creating feedbacks that either amplify or dampen regional climate changes. In the Amazon basin, for example, reduced evapotranspiration from deforested areas has been linked to decreased rainfall downwind, potentially creating a vicious cycle of forest loss and precipitation decline. Conversely, in some high-latitude regions, increased evapotranspiration from warming temperatures may enhance local moisture availability and cloud cover, potentially moderating temperature increases through increased albedo.

Soil moisture-precipitation coupling represents another critical feedback mechanism that can either buffer or amplify climate change impacts. Dry soils can suppress precipitation through various mechanisms, including reduced evapotranspiration (limiting atmospheric moisture), increased sensible heat flux (enhancing atmospheric stability), and changes in surface albedo. These effects can create positive feedbacks where drought conditions beget further drought, potentially leading to rapid transitions between ecosystem states. The concept of “hot droughts”—where warm temperatures compound precipitation deficits—has gained attention as researchers recognize that the same precipitation deficit can have vastly different impacts depending on temperature conditions. The 2012-2016 California drought, for example, was particularly severe because record warm temperatures increased evaporative demand, effectively making the precipitation deficit worse than it would have been under cooler conditions. Understanding these soil moisture-precipitation feedbacks

is crucial for predicting drought persistence and ecosystem vulnerability under climate change.

Vegetation dynamics and climate interactions create feedbacks that operate across time scales from seasons to centuries, as vegetation responds to climate changes and those responses in turn influence climate. On seasonal time scales, phenological changes in vegetation activity can influence surface energy balance and atmospheric heating patterns, potentially affecting regional circulation and precipitation. On decadal time scales, changes in species composition and forest structure can alter evapotranspiration rates and patterns, with consequences for water resources and climate

## 1.9 Agricultural Applications

As vegetation dynamics continue to reshape climate patterns through complex feedback mechanisms, the practical applications of evapotranspiration modeling become increasingly critical for one of humanity's most fundamental activities: agriculture. The sophisticated understanding of evapotranspiration processes that has emerged through decades of research does not remain confined to academic journals and research stations; it translates directly into practical tools that help farmers feed a growing global population while managing increasingly scarce water resources. The integration of evapotranspiration science into agricultural practice represents one of the most successful examples of how theoretical hydrological research can be transformed into tangible benefits for society, from smallholder farms in developing countries to high-tech agricultural operations in industrialized nations.

### 1.9.1 9.1 Irrigation Scheduling and Management

ET-based irrigation timing optimization has revolutionized water management in agriculture, moving irrigation decisions from art and intuition to science and precision. Traditional irrigation scheduling often relied on visual indicators of plant stress or fixed calendars, approaches that inevitably led to either underwatering (reducing yields) or overwatering (wasting water and leaching nutrients). Modern ET-based scheduling uses real-time evapotranspiration estimates to determine precisely when plants need water and how much they require. The University of California's California Irrigation Management Information System (CIMIS), established in 1982, represents one of the pioneering efforts in this domain. This network of over 145 automated weather stations provides reference evapotranspiration calculations that farmers can combine with crop coefficients to determine irrigation needs. The impact has been remarkable: studies have shown that CIMIS-based irrigation scheduling typically reduces water use by 15-25% while maintaining or even increasing crop yields, demonstrating that more precise water application can actually improve plant health by avoiding the oxygen deprivation and disease pressure that accompany overwatering.

Deficit irrigation strategies represent a more sophisticated application of ET modeling that intentionally applies less water than full crop evapotranspiration requirements, strategically timing water stress to minimize yield impacts while maximizing water savings. This approach recognizes that different crop growth stages have varying sensitivity to water stress and that some deficit can actually improve certain quality characteristics. In wine grape production, for example, controlled deficit irrigation during specific growth phases

can concentrate flavors and improve wine quality while reducing total water use by 20-40%. The pioneering work on regulated deficit irrigation in Australia during the 1980s demonstrated that carefully managed water stress could reduce irrigation requirements in peach orchards by up to 50% with minimal impact on fruit yield. Similar strategies have been successfully applied to cotton, where early-season water stress can actually promote more compact plant architecture that facilitates mechanical harvesting while reducing water requirements.

Partial root zone drying applications represent an innovative refinement of deficit irrigation that exploits plant physiological responses to uneven soil moisture conditions. This technique, developed in Australia during the 1990s, alternates irrigation between different sides of the plant root zone, maintaining part of the root system in moist soil while allowing other portions to dry. The drying roots produce chemical signals (particularly abscisic acid) that cause partial stomatal closure, reducing transpiration without severely limiting photosynthesis. Research on grapevines has shown that partial root zone drying can reduce water use by 40-50% while maintaining yield, with added benefits of reduced vegetative growth and improved fruit quality. The method has been successfully adapted to numerous other crops, including citrus, olives, and various vegetable crops, demonstrating how understanding the physiological basis of drought response can lead to more efficient water use strategies.

Automated irrigation systems integration with ET modeling has created the next generation of “smart” irrigation that can respond to changing conditions in real-time. Modern center pivot irrigation systems, for example, can be equipped with variable rate irrigation capabilities that apply different amounts of water to different parts of a field based on variations in soil type, topography, and crop water requirements. These systems often integrate weather station data, soil moisture sensors, and satellite observations to calculate actual evapotranspiration rates for different management zones within a field. One remarkable example comes from the Texas High Plains, where automated irrigation systems using ET modeling have helped reduce irrigation withdrawals from the Ogallala Aquifer by up to 30% while maintaining cotton yields. The integration of predictive weather forecasts allows these systems to anticipate irrigation needs days in advance, optimizing irrigation timing to avoid watering before rainfall events and adjusting applications based on expected evaporative demand.

## 1.9.2 9.2 Crop Water Requirements

Crop coefficient development and calibration represents one of the foundational applications of ET science in agriculture, bridging the gap between reference evapotranspiration from standardized surfaces and actual water needs of specific crops. The Food and Agriculture Organization has been at the forefront of this work, developing comprehensive crop coefficient datasets that cover virtually all major agricultural crops worldwide. These coefficients, typically denoted as  $K_c$  values, represent the ratio of crop evapotranspiration to reference evapotranspiration and vary throughout the growing season as crops develop from seedling to maturity. The development of reliable  $K_c$  values requires extensive field research using lysimeters and other direct measurement techniques, with the University of California’s Davis campus maintaining one of the world’s most comprehensive crop coefficient research programs. Their work has revealed fascinating

details about crop water use, such as the discovery that some modern wheat varieties have 10-15% lower water requirements than older varieties due to improved transpiration efficiency.

Growth stage-specific water needs recognition has transformed irrigation management by acknowledging that crops have dramatically different water requirements during different developmental phases. Most crops follow a characteristic pattern: relatively low water requirements during initial establishment, rapidly increasing needs during vegetative growth and reproductive development, followed by declining requirements as crops mature. The FAO has formalized this understanding by defining four distinct growth stages (initial, crop development, mid-season, and late season) with corresponding crop coefficient curves for each major crop. This detailed understanding allows farmers to prioritize water allocation during critical periods, such as the flowering and fruit set stages in many crops when water stress can cause disproportionate yield losses. Research on corn in Nebraska, for example, has shown that water stress during the two-week pollination period can reduce yields by up to 50%, while similar stress during vegetative growth stages typically causes yield reductions of only 10-20%.

Multiple cropping systems planning has benefited enormously from ET modeling, particularly in regions where farmers grow two or more crops per year on the same land. In double-cropping systems, such as the wheat-soybean rotations common in Argentina and the southern United States, ET modeling helps optimize planting dates and variety selections to ensure that water requirements of successive crops align with seasonal water availability. The International Water Management Institute has used ET modeling to demonstrate that double-cropping systems in the Indo-Gangetic Plain could increase total food production by 30-40% while using only 15-20% more water compared to single-cropping systems, representing a dramatic improvement in water productivity. These systems require careful management of soil moisture carryover between crops, with ET modeling providing the quantitative framework needed to ensure that water use by the first crop doesn't compromise the success of the second crop.

Greenhouse ET considerations present unique challenges that have led to specialized modeling approaches accounting for the modified environment within protected structures. Greenhouses typically have higher temperatures, different humidity patterns, and reduced wind speeds compared to open fields, all of which influence evapotranspiration rates. Research in the Netherlands, a global leader in greenhouse production, has developed sophisticated ET models specifically for greenhouse conditions that account for factors such as ventilation rates, screening materials, and supplemental lighting. These models have become increasingly important as greenhouse production expands globally, particularly in water-scarce regions where the water efficiency of greenhouse production can offset the higher energy costs. Studies have shown that well-managed greenhouse systems can achieve water productivity values 3-5 times higher than open-field agriculture, though this advantage depends critically on precise irrigation scheduling based on accurate ET estimates.

### 1.9.3 9.3 Precision Agriculture Integration

Variable rate irrigation applications represent one of the most promising frontiers where ET modeling meets high-tech agriculture, enabling water application to be matched precisely to spatial variability within fields.

This approach recognizes that even within apparently uniform fields, factors such as soil texture variations, topography, and historical yield patterns create significant differences in crop water requirements. Modern variable rate irrigation systems use GPS technology and sophisticated control systems to apply different amounts of water to different parts of a field as the irrigation equipment moves across it. The University of Nebraska's pioneering work on variable rate irrigation has demonstrated water savings of 15-25% in center-pivot irrigated corn fields, with the greatest benefits occurring on fields with the most soil variability. The integration of ET modeling with soil mapping technologies allows these systems to account not only for spatial differences in soil water-holding capacity but also for variations in crop water use patterns that emerge from these soil differences.

Site-specific ET mapping has been revolutionized by the convergence of satellite remote sensing, unmanned aerial vehicles (UAVs), and ground-based sensor networks. High-resolution satellite imagery from systems like Sentinel-2 and Planet can provide vegetation indices and surface temperature information at 10-meter resolution, while UAV-mounted thermal cameras can achieve even finer resolution of 5-10 centimeters. When combined with ground-based weather stations and soil moisture sensors, these observations can be processed through energy balance models to create detailed ET maps that show water use patterns across individual fields. The NASA DEVELOP program has worked with farmers in California's Central Valley to implement such systems, revealing water use variations of up to 40% across single fields due to soil and management differences. These detailed maps allow farmers to identify problem areas where water use is inefficient and to target interventions such as soil amendment or drainage improvements.

Yield prediction and water productivity optimization has emerged as a valuable application of ET modeling that helps farmers make informed decisions about irrigation investments. By tracking cumulative evapotranspiration throughout the growing season and comparing it to historical yield patterns, farmers can develop predictive relationships between water use and crop productivity for their specific fields. This approach has been particularly valuable in regions where water availability limits production, helping farmers determine the optimal amount of irrigation to maximize economic returns rather than simply physical yields. Research in the Colorado River Basin has shown that many farmers could achieve 90-95% of maximum yield while using only 75-80% of full water requirements, representing significant water savings with relatively small yield penalties. These analyses become increasingly important as water markets develop and farmers face decisions about whether to use water for crop production or to sell it to other users.

Economic optimization of water use represents the ultimate integration of ET science with farm management, acknowledging that irrigation decisions should balance water costs, crop prices, and yield responses to determine the most profitable water application strategy. This approach requires understanding not just the physical relationship between water use and yield, but also how this relationship varies with crop prices, water costs, and risk tolerance. Agricultural economists at Texas A&M University have developed sophisticated decision support tools that incorporate ET modeling, crop yield response functions, and economic variables to help farmers determine optimal irrigation strategies. These tools have revealed counterintuitive insights, such as situations where applying less water than the crop technically needs can increase profitability when water costs are high or crop prices are low. The integration of ET science with economics represents a crucial step toward sustainable water management in agriculture, ensuring that water use decisions consider



both physical efficiency and economic viability.

#### 1.9.4 9.4 Water Resource Management

Basin-scale water allocation has been transformed by the application of ET modeling at watershed and regional scales, providing the scientific foundation for more equitable and efficient water distribution systems. The Colorado River Basin, for example, uses sophisticated ET models combined with remote sensing to track water use throughout the basin, informing the complex system of water allocations that serves 40 million people across seven states. The OpenET initiative, launched in 2020, provides publicly accessible ET data for the western United States, enabling water managers, farmers, and policymakers to make decisions based on consistent, transparent information about water consumption. These basin-scale applications of ET modeling have revealed surprising patterns, such as the discovery that agricultural water use in some areas is significantly higher or lower than official estimates based on water rights, leading to reforms in water accounting and management practices.

Water rights and ET-based accounting is revolutionizing how water resources are measured and managed in legal and institutional frameworks. Traditional water rights systems often relied on crude measurements of water diverted from streams or rivers, ignoring the fact that much of this water might return to the system through runoff or deep percolation. Modern ET-based accounting provides a more accurate measure of consumptive water use—the water actually removed from the system through evapotranspiration. The state of Texas has been a leader in implementing ET-based water rights administration, using satellite-derived ET estimates to verify that water users stay within their authorized consumptive use limits. This approach has resolved long-standing disputes over water measurements and provides a more scientifically defensible basis for water rights enforcement, though it requires sophisticated technical capacity and institutional adaptation.

Groundwater pumping optimization has become increasingly critical as aquifer depletion threatens agricultural sustainability in many regions worldwide. ET modeling helps determine optimal pumping rates by balancing crop water requirements with aquifer recharge rates and sustainable yield considerations. The High Plains Aquifer (Ogallala) system, which underlies portions of eight states and provides irrigation water for one-quarter of U.S. agricultural production, has been a particular focus of ET-informed groundwater management. Research using ET models has shown that converting from high-water-use crops like corn to less water-intensive alternatives like sorghum or wheat could extend the usable life of portions of the aquifer by decades while maintaining farm profitability. These studies have informed policy discussions about groundwater management districts and conservation programs, demonstrating how ET science can guide difficult decisions about agricultural transitions in water-scarce regions.

Drought preparedness planning has been enhanced through the integration of ET modeling with seasonal climate forecasts, allowing water managers to anticipate and prepare for water shortages before they become crises. The U.S. Drought Monitor, established in 1999, incorporates ET estimates along with precipitation, soil moisture, and other indicators to provide comprehensive assessments of drought conditions. More recently, researchers have developed forecast systems that use seasonal climate predictions to estimate likely ET conditions months in advance, giving water managers lead time to implement conservation measures,



adjust reservoir operations, or assist farmers in cropping decisions. The California Department of Water Resources uses such forecasts in its Drought Contingency Planning, allowing for more proactive rather than reactive drought management. These forecasting capabilities become increasingly valuable as climate change increases the frequency and intensity of drought conditions in many agricultural regions.

### 1.9.5 9.5 Climate-Smart Agriculture

Resilient cropping system design represents a proactive application of ET modeling to prepare agriculture for the challenges of climate change, including higher temperatures, altered precipitation patterns, and increased evaporative demand. This approach involves selecting crop combinations, rotation patterns, and management practices that maintain productivity under a wider range of climate conditions. The Consultative Group on International Agricultural Research (CGIAR) has used ET modeling extensively in developing climate-resilient cropping systems for smallholder farmers in Africa, Asia, and Latin America. In the Sahel region of Africa, for example, ET modeling has helped design intercropping systems that combine deep-rooted trees with shallow-rooted annual crops, creating more efficient use of available soil moisture throughout the soil profile. These agroforestry systems can maintain productivity during dry periods while providing additional benefits such as soil improvement and fodder production.

Water-efficient cultivar selection has been accelerated through the integration of ET modeling with plant breeding programs, allowing breeders to identify and develop crop varieties that maintain productivity with less water. The International Maize and Wheat Improvement Center (CIMMYT) has used ET modeling and phenotyping platforms to identify wheat lines with improved transpiration efficiency—the ratio of carbon assimilation to water loss. These breeding efforts have produced varieties that maintain yields with 10-15% less water under drought conditions, representing significant improvements in water productivity. Similar programs have targeted other staple crops, including rice, where alternate wetting and drying irrigation systems combined with water-efficient varieties can reduce water requirements by 30-50% while maintaining yields. These breeding achievements demonstrate how understanding the physiological basis of water use can translate directly into genetic improvements that benefit farmers worldwide.

Conservation agriculture impacts on ET have revealed how soil management practices can influence water availability to crops through changes in evapotranspiration patterns. Conservation agriculture, which includes minimum tillage, crop residue retention, and diverse crop rotations, typically increases soil organic matter and improves soil structure, affecting both soil water storage and evaporation rates. Long-term research in Brazil's Cerrado region has shown that conservation agriculture systems can reduce soil evaporation by 20-30% while increasing transpiration efficiency, effectively making more water available for crop growth. The residue mulch layer characteristic of conservation agriculture systems reduces evaporation from the soil surface while the improved soil structure enhances root development and water extraction from deeper soil layers. These effects become particularly valuable under climate change conditions, as conservation agriculture systems generally maintain higher yields under drought stress compared to conventional tillage systems.

Agroforestry system water balance represents one of the most complex applications of ET modeling, as these

intentional combinations of trees, crops, and sometimes livestock create intricate interactions that influence water cycling. The World Agroforestry Centre (ICRAF) has conducted extensive research on how different agroforestry designs affect evapotranspiration patterns and

## **1.10 Urban and Ecological Applications**

As we shift our focus from the carefully managed agricultural fields that feed humanity to the complex mosaic of urban and natural ecosystems that sustain our planet, the importance of evapotranspiration modeling only becomes more apparent. The sophisticated understanding of water vapor transfer that has revolutionized irrigation scheduling and crop water productivity now finds equally compelling applications in contexts where human water needs intersect with ecological requirements. From the heat-stressed streets of megacities to the pristine watersheds that supply drinking water to millions, evapotranspiration processes shape the availability, quality, and distribution of water resources in ways that directly affect human welfare and ecosystem health. The application of ET science in these broader contexts represents not just an expansion of our technical capabilities but a fundamental recognition that water cycling connects all aspects of Earth's systems, from the smallest urban garden to the largest river basin.

### **1.10.1 10.1 Urban Water Management**

Green infrastructure ET quantification has emerged as a critical tool for sustainable urban development as cities worldwide grapple with the combined challenges of urbanization, climate change, and water scarcity. Green roofs, for example, have become increasingly popular in cities from Chicago to Stuttgart, yet their effectiveness depends critically on understanding and optimizing their evapotranspiration rates. Research at Columbia University's Urban Design Lab has demonstrated that well-designed green roofs can return 50-70% of incident rainfall to the atmosphere through evapotranspiration, substantially reducing stormwater runoff volumes. The sophistication of this modeling has advanced to the point where designers can optimize substrate depth, vegetation selection, and irrigation systems to maximize ET benefits while ensuring plant survival under urban conditions. The Javits Center green roof in New York City, one of the largest in the United States at nearly 7 acres, serves as a living laboratory where ET measurements have helped refine design guidelines for similar installations worldwide, demonstrating how urban infrastructure can simultaneously address stormwater management, heat island mitigation, and biodiversity conservation.

Urban forest cooling benefits represent one of the most compelling applications of ET science in cities, where transpiration from trees can reduce local temperatures by 1-3°C compared to exposed surfaces. The U.S. Forest Service's i-Tree software suite incorporates sophisticated ET models to quantify these cooling benefits, allowing city planners to prioritize tree planting where they will have the greatest impact on energy consumption and human comfort. Studies in Los Angeles have shown that strategic urban tree planting could reduce air conditioning demand by up to 30% in some neighborhoods, with equivalent energy savings valued at millions of dollars annually. The complexity of urban ET modeling in these contexts requires accounting for unique urban conditions including the urban canyon effect that alters wind patterns, the heat island that

increases evaporative demand, and the restricted soil volumes that limit root growth and water availability. Despite these challenges, advances in modeling have enabled cities to develop urban forest master plans that optimize species selection and placement to maximize ET-based cooling while considering maintenance requirements and infrastructure conflicts.

Stormwater management system design has been revolutionized by the integration of ET modeling, particularly as cities move toward green infrastructure approaches that mimic natural water cycling. Traditional stormwater systems focused on rapid conveyance of rainfall away from urban areas, often creating downstream flooding and water quality problems. Modern approaches, exemplified by Philadelphia's Green City, Clean Waters program, use ET modeling to design systems that capture, store, and evaporate stormwater on site. These systems include rain gardens, bioswales, and permeable pavements that rely on evapotranspiration to remove water from the system between storm events. The design challenge involves understanding the seasonal and daily patterns of ET capacity and ensuring that storage volumes are sized appropriately for local climate conditions. Philadelphia's program has demonstrated that green infrastructure can reduce combined sewer overflows by billions of gallons annually while providing additional benefits including improved air quality, increased property values, and enhanced urban biodiversity.

Municipal water demand forecasting has become increasingly sophisticated as water utilities recognize that outdoor water use, primarily for landscape irrigation, often represents the largest component of residential demand in arid and semi-arid cities. The Southern Nevada Water Authority, serving Las Vegas, has developed one of the most advanced ET-based demand forecasting systems in the world, integrating satellite-derived ET estimates with customer billing data to predict water use at the neighborhood scale. Their system accounts for the complex factors that drive irrigation demand, including reference evapotranspiration, precipitation, lot size, vegetation type, and even socioeconomic factors that influence water use behavior. During the severe drought from 2000-2005, this forecasting system helped the authority achieve a 30% reduction in per capita water use while maintaining the quality of urban landscapes, demonstrating how ET science can support both conservation goals and livability objectives. The authority's Water Smart Landscape program, which pays homeowners to replace water-intensive turf with desert-adapted vegetation, uses ET modeling to quantify water savings and optimize program effectiveness.

### **1.10.2 10.2 Forest Water Cycling**

Watershed-scale ET estimation has transformed our understanding of how forests influence water availability for downstream users, challenging historical assumptions about forest-water relationships that often guided management decisions. The classic view, held through much of the 20th century, was that forests reduced water yields through high transpiration rates, leading to widespread forest clearing in some watersheds to increase water supply. Modern ET research, however, has revealed a far more nuanced picture that varies with forest type, age, climate, and management history. The Hubbard Brook Experimental Forest in New Hampshire has provided some of the longest continuous measurements of forest ET, beginning in the 1950s and revealing that mature northern hardwood forests typically return 40-50% of precipitation to the atmosphere through evapotranspiration. These measurements have been crucial for calibrating watershed models

that now inform forest management decisions across the northeastern United States, where water utilities often own forested watershed lands specifically to protect water quality and regulate flows.

Forest management impacts on water yield represent one of the most practical applications of ET science, as managers seek to balance timber production, biodiversity conservation, and water provision. Research in the Sierra Nevada mountains of California has demonstrated that different forest management practices can have dramatically different effects on ET and water yield. A study by the U.S. Forest Service found that thinning overly dense forests reduced stand-level ET by 15-25% and increased streamflow by equivalent amounts, with the greatest benefits occurring when thinning targeted smaller trees and was followed by prescribed burning. These findings have informed California's forest management policies, particularly as the state seeks to increase water yield from its forested watersheds while reducing wildfire risk. The complexity of these relationships requires understanding how management affects not just total leaf area but also the distribution of leaves within the canopy, the species composition of the regenerating forest, and the interactions with snow accumulation and melt patterns that dominate the water balance in many mountainous regions.

Age and species composition effects on forest ET have revealed fascinating patterns that challenge simple assumptions about forest water use. Young, rapidly growing forests typically have higher transpiration rates per unit leaf area than mature forests, but their total water use may be lower due to smaller total leaf area. As forests age, they typically develop more complex canopy structures with greater leaf area indices, but individual leaves become less efficient at water use due to hydraulic limitations and shading effects. Research in the Pacific Northwest has shown that old-growth Douglas-fir forests can have similar or even lower total ET rates than younger stands, despite having much greater biomass, because the complex multi-layered canopy structure and prevalence of shaded leaves reduce overall transpiration efficiency. Similarly, species composition matters tremendously, with coniferous forests typically maintaining higher winter ET rates than deciduous forests due to their year-round foliage, while broadleaf deciduous forests often have higher peak summer ET rates. These nuances are crucial for understanding how forest succession, species migration under climate change, and management decisions will influence water availability in forested watersheds.

Disturbance and recovery ET dynamics have become increasingly important as forests worldwide experience more frequent and severe disturbances from wildfire, insect outbreaks, and extreme weather events. The 2013 Rim Fire in California's Sierra Nevada provided a natural experiment in how forest ET responds to and recovers from severe disturbance. Measurements using eddy covariance towers before and after the fire revealed immediate reductions in ET of 60-80% as the forest canopy was consumed, followed by a gradual recovery over decades as vegetation regrew. The rate of ET recovery varied with elevation and severity of burn, with some areas still showing reduced ET rates ten years after the fire. Similar patterns have been documented following insect outbreaks, such as the mountain pine beetle epidemic that has affected millions of hectares of forest in western North America. These disturbance-recovery dynamics have important implications for water resources, potentially increasing water yield in the short term but affecting the timing and reliability of flows as vegetation communities change. Understanding these patterns helps water managers anticipate the hydrological consequences of forest disturbances and develop adaptive management strategies.

### 1.10.3 10.3 Wetland Hydrology

Evapotranspiration in wetland water balance represents one of the most challenging yet important applications of ET science, as wetlands often have ET rates that exceed precipitation inputs, making them dependent on groundwater or surface water inflows to maintain their hydrological character. The Florida Everglades provide a dramatic example of these dynamics, where long-term measurements have shown that ET typically exceeds rainfall by 200-400 millimeters annually, creating a water deficit that must be supplied by the slower moving sheet flow from Lake Okeechobee. The Everglades restoration effort, one of the largest ecosystem restoration projects in the world, depends critically on accurate ET estimates to design water management structures that will replicate natural flow patterns. The complexity of wetland ET stems from the heterogeneous nature of these systems, with open water, emergent vegetation, and forested wetlands each having different ET characteristics that vary seasonally with water depth and vegetation phenology. The Everglades Depth Estimation Network (EDEN) incorporates sophisticated ET models that account for these spatial and temporal variations, providing the scientific foundation for restoration decisions that will affect millions of people and countless species.

Phreatophyte water use patterns represent a specialized but crucial aspect of wetland hydrology, particularly in arid and semi-arid regions where deep-rooted plants tap directly into groundwater resources. The term “phreatophyte” refers to plants whose roots reach the water table, allowing them to maintain transpiration even when surface soils are dry. Research along the San Pedro River in southeastern Arizona has quantified the water use of riparian phreatophytes such as cottonwood and willow trees using techniques including sap flow measurements, stable isotope analysis, and groundwater monitoring. These studies have revealed that a single mature cottonwood tree can transpire up to 200 liters of water per day during peak growing season, with riparian corridors sometimes accounting for 30-40% of total groundwater discharge in small watersheds. The implications for water management are profound, as decisions to remove or restore riparian vegetation can significantly impact groundwater levels and surface water flows. In Nevada’s Walker River Basin, water managers have used ET models to estimate that phreatophyte removal could yield up to 30,000 acre-feet of water annually, though they must balance these potential water savings against the ecological benefits of riparian ecosystems.

Restoration project monitoring has been transformed by the application of ET science, providing quantitative metrics to assess the success of wetland restoration efforts and guide adaptive management. The Tidal Wetland Restoration Program in San Francisco Bay employs comprehensive ET monitoring to understand how restored wetlands re-establish their water balance functions following decades of agricultural use. Measurements using eddy covariance towers, combined with remote sensing and groundwater monitoring, have revealed that restored wetlands initially have higher ET rates than natural wetlands due to the vigorous growth of early successional species, with rates gradually declining over decades as plant communities mature and hydraulic connections develop. These findings have important implications for restoration planning, as high ET rates in newly restored wetlands can affect water availability for other uses and may require additional water allocations during the establishment phase. The monitoring program also uses ET measurements to evaluate the effectiveness of different restoration techniques, from contour grading to vegetation planting,

providing evidence-based guidance for future restoration projects.

Methane emission interactions with ET represent a frontier area of research that connects wetland hydrology to global climate dynamics, as the same saturated conditions that support high ET rates in wetlands also create anaerobic environments conducive to methane production and emission. Research in the Sacramento-San Joaquin Delta of California has revealed complex relationships between water depth, vegetation type, ET rates, and methane emissions that challenge simple assumptions about wetland climate impacts. Deep water wetlands typically have lower ET rates but higher methane emissions per unit area, while shallow wetlands with emergent vegetation have higher ET but lower methane fluxes. The net climate effect depends on the relative global warming potential of water vapor versus methane emissions over different time horizons. These findings have important implications for wetland restoration and creation projects designed to sequester carbon, as the climate benefits of carbon storage must be balanced against methane emissions and the cooling effects of ET. This research highlights the need for integrated assessments that consider multiple greenhouse gases and the complex ways that wetland management influences climate dynamics.

#### **1.10.4 10.4 River Basin Management**

Integrated water resources management has been fundamentally transformed by the availability of basin-scale ET estimates that provide consistent, comprehensive information about water consumption across entire watersheds. The Murray-Darling Basin in Australia, which drains one-seventh of the Australian continent and supports 40% of agricultural production, has implemented one of the world's most sophisticated water accounting systems based on satellite-derived ET measurements. The basin's Sustainable Diversion Limits, established in 2012, use ET data from the OpenET platform to track water use by individual irrigators, ensuring that total consumptive use stays within environmentally sustainable limits. This system has resolved long-standing conflicts over water measurements and allocations by providing transparent, scientifically defensible data on actual water consumption rather than water diversions. The success of the Murray-Darling approach has inspired similar initiatives in other water-stressed basins worldwide, from the Colorado River Basin in North America to the Indus Basin in South Asia, demonstrating how ET science can provide the foundation for more equitable and sustainable water governance.

Environmental flow requirements represent one of the most critical applications of ET science in river basin management, as ensuring sufficient water for ecosystems depends on understanding how much water is naturally consumed through evapotranspiration within the basin. The South African Water Act of 1998 pioneered the formal recognition of the "Reserve" – the water quantity and quality required to maintain basic ecological functions – in national water law. Implementing this requirement has depended on sophisticated ET modeling to determine how much water must remain in rivers to support downstream ecosystems after accounting for upstream consumptive uses. The Working for Water program, which removes invasive alien plant species to reduce water consumption, uses ET models to prioritize removal activities based on their potential water yield benefits. Research has shown that invasive species like eucalyptus and black wattle can increase ET by 200-500 millimeters annually compared to native vegetation, representing substantial water savings when these species are removed. The program has cleared over one million hectares of invasive vegetation, with



estimated water savings sufficient to supply millions of people, demonstrating how ecosystem restoration can simultaneously achieve environmental and water supply objectives.

Inter-basin water transfer assessments have become increasingly sophisticated as planners recognize that moving water between basins inevitably involves not just the physical transfer of water but also the disruption of natural ET patterns and atmospheric moisture recycling. The South-to-North Water Transfer Project in China, the largest such project ever undertaken, involves three massive canals moving water from the water-rich south to the arid north. Comprehensive ET modeling was essential for assessing the full impacts of this project, including not just the direct water transfers but also the changes in ET patterns that would result from altered land use and water availability in both source and receiving basins. The assessments revealed that reducing water availability in source basins would decrease ET and local atmospheric moisture, potentially reducing downwind precipitation in a cascade of effects that extend far beyond the immediate project area. Similarly, increasing water availability in receiving basins would enhance ET, potentially moderating local temperatures but also increasing humidity and affecting regional climate patterns. These complex considerations highlight how large-scale water engineering projects must account for ET processes to understand their full range of environmental impacts.

Transboundary water conflict resolution has increasingly relied on neutral, scientific information about ET patterns to facilitate negotiations between countries sharing water resources. The Indus River Basin, shared by India, Pakistan, Afghanistan, and China, has been the focus of international efforts to use satellite-derived ET data to improve water sharing arrangements under the Indus Waters Treaty of 1960. The treaty divides the rivers between India and Pakistan but was based on limited hydrological understanding when it was negotiated. Modern ET measurements have revealed that actual consumptive use differs substantially from what was assumed when the treaty was signed, creating opportunities for more efficient and equitable water sharing. The World Bank's Indus Basin Initiative has used remote sensing to map ET patterns across the basin, providing objective information that can support technical discussions between the countries. Similar efforts are underway in other transboundary basins, including the Nile, Jordan, and Mekong, where ET science provides a common technical foundation for addressing complex political and social issues around water sharing.

#### **1.10.5 10.5 Ecosystem Services Valuation**

ET-based ecosystem service quantification has emerged as a powerful approach to communicating the value of natural systems to decision makers and the public, translating complex hydrological processes into economic terms that can be incorporated in planning and policy decisions. The concept of ecosystem services recognizes that natural systems

### **1.11 Computational Challenges and Solutions**

The sophisticated applications of evapotranspiration modeling across urban and natural ecosystems, as we've explored throughout this section, rest upon a foundation of computational science that faces numerous tech-

nical and methodological challenges. These challenges are not merely academic hurdles but practical limitations that directly affect our ability to apply ET science to real-world problems. The gap between theoretical understanding and practical application narrows only through persistent innovation in computational methods, data management, and modeling approaches. As we increasingly rely on evapotranspiration models to address pressing challenges from water scarcity to climate change adaptation, the importance of understanding and overcoming these computational challenges becomes ever more critical. The solutions to these challenges, developed through decades of collaborative research and innovation, represent some of the most significant advances in hydrological computing and continue to shape the future of evapotranspiration science.

### 1.11.1 11.1 Data Requirements and Availability

Meteorological data gaps and quality issues represent perhaps the most fundamental challenge facing evapotranspiration modelers worldwide, as even the most sophisticated algorithms cannot produce reliable results without accurate input data. The World Meteorological Organization's Global Observing System, comprising over 10,000 surface stations, provides an impressive foundation for global ET modeling, yet substantial gaps remain, particularly in developing regions and remote areas. The African continent, for example, has only about one-eighth the density of weather stations compared to Europe and North America, creating vast areas where ET modeling must rely on interpolated or estimated meteorological data. This data scarcity becomes particularly problematic during extreme events when accurate ET estimates are most needed for drought and flood management. The 2015-2016 El Niño event highlighted this challenge, as many Pacific Island nations lacked the comprehensive weather monitoring needed to assess evapotranspiration changes during this major climate disruption, complicating both emergency response and longer-term adaptation planning.

Spatial interpolation challenges emerge when attempting to create continuous meteorological fields from point measurements, a process essential for many ET applications that require spatially distributed data. The complexity of this task becomes apparent when considering the dramatic variations that can occur over short distances, particularly in mountainous regions where elevation changes create microclimates with distinct evapotranspiration regimes. Traditional interpolation methods like inverse distance weighting and kriging often struggle with these complex terrains, leading to errors in estimated solar radiation, temperature, and humidity that propagate through ET calculations. Researchers in the Rocky Mountains have documented elevation-related temperature lapse rates that vary seasonally and with atmospheric conditions, creating challenges for simple elevation-based temperature adjustments. More sophisticated approaches incorporating terrain aspect, slope, and cold air drainage patterns have improved interpolation accuracy but require substantially more computational resources and detailed digital elevation models, creating trade-offs between accuracy and practicality for operational applications.

Temporal resolution requirements vary dramatically among different ET applications, creating challenges for data collection and processing systems that must serve diverse user needs. Real-time irrigation scheduling may demand hourly ET estimates, while climate change assessments might require daily values aggregated

over decades. The challenge becomes particularly acute when working with satellite observations, where revisit times and cloud cover create irregular temporal sampling patterns. The MODIS sensors, for example, provide daily observations but frequent cloud cover in tropical regions means that actual clear-sky observations might only occur every 8-16 days. Researchers at the University of Alaska have developed sophisticated temporal gap-filling algorithms that can reconstruct daily ET patterns from irregular satellite observations by incorporating information about vegetation phenology and climate patterns. These approaches have enabled consistent ET time series even in persistently cloudy regions like the Amazon basin, though they introduce additional uncertainty that must be quantified and communicated to users.

Open data initiatives and sharing platforms have emerged as powerful solutions to data availability challenges, transforming how researchers and practitioners access the meteorological and satellite data needed for ET modeling. The NASA Earth Observing System Data and Information System (EOSDIS), for example, provides free access to petabytes of Earth observation data that previously required expensive subscriptions or specialized processing capabilities. Similarly, the Copernicus program managed by the European Space Agency has made Sentinel satellite data freely available to users worldwide, dramatically reducing the cost barrier for high-resolution ET monitoring. These open data initiatives have democratized access to ET modeling capabilities, enabling applications from smallholder irrigation management in Kenya to watershed planning in Romania. However, the sheer volume of available data creates new challenges in data management, processing, and interpretation, leading to the development of specialized platforms like Google Earth Engine that provide cloud-based processing capabilities optimized for large-scale Earth observation analysis.

### 1.11.2 11.2 Scale Issues and Upscaling

Point to pixel scale discontinuities represent one of the most persistent challenges in evapotranspiration modeling, arising from the fundamental mismatch between the scale at which we can make direct measurements and the scale at which we often need ET information. An eddy covariance tower, for example, typically measures fluxes over an area of a few hundred meters to a few square kilometers, depending on measurement height and wind conditions, while satellite pixels might cover areas from 30 meters (Landsat) to several kilometers (MODIS). This scale mismatch creates what researchers term the “footprint problem” – the difficulty of determining exactly what surface area contributed to a particular measurement. The FLUXNET network has developed sophisticated footprint models that help relate point measurements to surrounding land cover, but these models require detailed information about atmospheric stability, wind patterns, and surface roughness that are often unavailable. The challenge becomes particularly acute in heterogeneous landscapes where different land cover types within a single pixel can have dramatically different ET rates, violating the assumption of surface homogeneity that underlies many retrieval algorithms.

Spatial heterogeneity representation challenges modelers to capture the complex mosaic of land cover, soil types, and topographic positions that influence evapotranspiration patterns across real landscapes. Even apparently uniform agricultural fields often contain significant variability in soil properties, drainage patterns, and microclimate that affect ET rates. Research in Nebraska’s Sandhills region has revealed that variations in soil depth of just a few centimeters across sand dunes can create differences in ET rates of 20-30% due

to variations in water availability to vegetation. Capturing this fine-scale heterogeneity requires either very high-resolution remote sensing data or sophisticated sub-grid parameterization schemes that represent the statistical distribution of surface properties within each model grid cell. The National Ecological Observatory Network (NEON) in the United States is addressing this challenge through its design, which places measurement towers in homogeneous areas but surrounds them with distributed sensor arrays that capture spatial variability, providing the data needed to develop and validate scaling approaches.

Temporal scaling from instantaneous to daily periods presents another set of challenges, particularly when working with satellite observations that provide only snapshots of surface conditions at specific times of day. The diurnal cycle of evapotranspiration typically follows a bell-shaped curve, peaking in early afternoon and declining to near zero at night, but the exact shape and timing of this curve varies with weather conditions, vegetation type, and soil moisture availability. Simple approaches that multiply instantaneous measurements by a constant factor to estimate daily totals can introduce substantial errors, particularly on days with variable cloud cover or rapidly changing weather conditions. Researchers at Oregon State University have developed more sophisticated approaches that use diurnal temperature curves and vegetation characteristics to reconstruct the full daily ET cycle from limited observations. These methods have proven particularly valuable for thermal infrared approaches like SEBAL and METRIC, which typically rely on a single satellite overpass per day but need to estimate total daily ET for irrigation scheduling and water management applications.

Multi-scale validation approaches have emerged as essential tools for assessing how well ET models perform across the range of spatial and temporal scales required for different applications. The Triple Collocation technique, for example, allows researchers to assess the accuracy of three independent ET datasets simultaneously without requiring any one of them to be treated as a “truth” reference. This approach has been applied to compare satellite-derived ET products, process-based model simulations, and ground-based measurements, revealing systematic scale dependencies in model performance. Similarly, the International Land Model Benchmarking (ILAMB) project has developed standardized procedures for evaluating models across multiple scales and metrics, creating a more comprehensive picture of model strengths and limitations than traditional single-point validation approaches. These multi-scale validation efforts have revealed that models that perform well at daily time scales may struggle with seasonal or annual patterns, while models optimized for regional averages might miss important local variations, highlighting the importance of matching model complexity and scale to specific application needs.

### 1.11.3 11.3 Parameter Uncertainty and Sensitivity

Calibration data requirements present a substantial challenge for many process-based ET models, particularly those with numerous parameters that must be estimated from limited observations. The Penman-Monteith equation, while theoretically elegant, requires accurate estimation of surface resistance and aerodynamic resistance, parameters that vary with vegetation type, phenology, and environmental conditions. In practice, these parameters are often estimated through calibration against measured ET data, creating a circular dependency where good measurements are needed to obtain good measurements. This challenge becomes particularly acute in data-sparse regions where flux towers or lysimeters are unavailable, forcing modelers to

rely on parameter values from similar ecosystems that may not actually be appropriate for local conditions. The International Soil Moisture Network has helped address this challenge by creating a global database of soil hydraulic properties that can be used to estimate soil resistance parameters, but substantial uncertainty remains, particularly for less-studied ecosystems and vegetation types.

Parameter identifiability issues emerge when different parameter combinations produce similar model outputs, making it difficult to determine which parameter values are actually correct based on calibration data alone. This problem is particularly common in complex ET models with multiple interacting parameters that can compensate for each other. For example, in some models, increasing stomatal conductance while decreasing leaf area index might produce similar transpiration rates to the opposite combination, creating an equifinality problem where multiple parameter sets are equally consistent with available data. Researchers at the University of Edinburgh have developed sophisticated identifiability analysis techniques that help determine which parameters can be reliably estimated from available data and which remain uncertain. These analyses have revealed that even with comprehensive measurement campaigns, some parameters in complex ET models remain poorly constrained, suggesting the need for either additional measurements or simplified model structures that focus on the most important processes.

Monte Carlo uncertainty analysis has become an essential tool for quantifying how parameter uncertainty propagates through ET models to affect predictions, providing crucial information for decision makers who need to understand the reliability of model outputs. This approach involves running models thousands of times with different parameter values drawn from probability distributions representing parameter uncertainty, creating an ensemble of possible outcomes rather than a single deterministic prediction. The U.S. Geological Survey has applied Monte Carlo techniques to their national ET modeling efforts, creating maps of ET uncertainty that accompany their ET estimates. These uncertainty maps have revealed that prediction confidence varies substantially across space and time, with higher uncertainty in complex mountainous terrain and during periods of rapid vegetation change. Perhaps surprisingly, the analysis has also shown that the most complex models don't always produce the most certain predictions, as additional parameters can introduce additional sources of uncertainty that outweigh their theoretical improvements in process representation.

Bayesian calibration approaches represent a sophisticated alternative to traditional calibration methods that explicitly incorporate prior knowledge and quantify uncertainty in a statistically rigorous framework. Unlike traditional calibration that seeks a single "best" parameter set, Bayesian calibration produces posterior probability distributions for each parameter that represent what we know about the parameter after considering both prior information and calibration data. The Joint UK Land Environment Simulator (JULES) has implemented Bayesian calibration for its ET components, allowing researchers to combine information from laboratory measurements, field studies, and remote sensing observations in a unified statistical framework. These approaches have proven particularly valuable when working with multiple data types that provide complementary information about different aspects of the ET system. For example, thermal infrared remote sensing might provide strong constraints on surface energy balance while sap flow measurements constrain stomatal conductance, and Bayesian methods can optimally combine these different data streams to improve parameter estimates and reduce uncertainty.

#### 1.11.4 11.4 Computational Intensity

High-resolution modeling demands have escalated dramatically as users seek ET information at increasingly fine spatial and temporal scales to support precision agriculture, urban planning, and ecosystem management. Modeling ET at 30-meter resolution with daily time steps for a moderate-sized watershed can require processing terabytes of input data and performing billions of calculations, creating computational challenges that were unimaginable just a decade ago. The USDA's National Water and Climate Center has developed some of the most computationally intensive ET modeling systems in the world, producing daily 30-meter resolution ET maps for the entire United States. Their system processes over 10 terabytes of satellite data and weather observations each day, requiring a dedicated high-performance computing cluster with hundreds of processing cores. The challenge extends beyond just processing power to include data storage, transfer, and management, as the volume of intermediate files created during processing can be many times larger than the final products.

Parallel computing implementations have revolutionized ET modeling by enabling the distribution of computational tasks across multiple processors, dramatically reducing processing times for large-scale applications. The OpenET initiative, which produces ET data for the western United States, has implemented sophisticated parallel processing algorithms that allow different watersheds to be processed simultaneously on a computing cluster. This approach has reduced the time required to produce statewide ET maps from weeks to hours, enabling near-real-time applications that were previously impossible. The challenge with parallel processing lies in efficiently dividing the computational task while managing dependencies between different spatial areas. For example, watershed-scale ET models often need to consider upslope contributions and downstream effects, creating spatial dependencies that complicate parallel processing. Researchers have developed various domain decomposition approaches that balance computational load while minimizing these dependencies, but finding the optimal decomposition remains an active area of research, particularly for models with complex spatial interactions.

Cloud computing solutions have emerged as powerful alternatives to traditional high-performance computing clusters, offering scalable computing resources that can be rapidly provisioned and deprovisioned as needed. Google Earth Engine, in particular, has transformed how many researchers and practitioners approach large-scale ET analysis by providing access to Google's massive computing infrastructure along with a comprehensive archive of satellite data. Researchers at the University of Minnesota have used Earth Engine to process 35 years of Landsat data to analyze trends in ET across the Upper Mississippi River basin, a task that would have required years of processing on traditional computing systems. The pay-as-you-go pricing model of cloud computing makes it accessible even to small research groups and developing country institutions, though managing costs requires careful optimization of algorithms and data access patterns. The main challenge with cloud computing remains data transfer costs and security concerns, particularly when working with sensitive water resources data that cannot be transferred to commercial cloud environments.

Real-time processing challenges become particularly apparent when ET models are integrated into decision support systems that require rapid responses to changing conditions. Automated irrigation scheduling systems, for example, may need to process new weather data and produce updated ET recommendations multiple



times per day during critical growth stages. The California Department of Water Resources has developed one of the most sophisticated real-time ET processing systems in support of their drought response activities, ingesting data from over 150 weather stations and multiple satellite systems to produce continuously updated ET estimates. The technical challenges include not just computational speed but also data quality control, as erroneous sensor readings or satellite data gaps must be detected and corrected automatically without human intervention. These systems typically implement redundant processing pathways with multiple algorithms running in parallel, allowing the system to continue functioning even if one component fails, though this redundancy increases computational requirements and system complexity.

#### **1.11.5 11.5 Model Validation and Intercomparison**

Flux tower network limitations create fundamental challenges for ET model validation, as these expensive measurement systems can only provide information for limited locations and periods. The global FLUXNET network, while comprising over 500 towers worldwide, still provides sparse coverage relative to the diversity of ecosystems and climate conditions where ET models are applied. The towers are also disproportionately located in North America and Europe, with relatively few measurements from Africa, South America, and Asia despite their importance for global water cycling. Furthermore, flux towers typically measure fluxes over homogeneous areas, creating challenges for validating models in heterogeneous landscapes where different land cover types interact to determine aggregate ET rates. Researchers have addressed these limitations through targeted measurement campaigns that temporarily deploy flux towers in underrepresented ecosystems, such as the SAFARI 2000 campaign in Africa that provided valuable ET data from savanna and woodland ecosystems. However, these temporary campaigns cannot replace the need for long-term, continuous measurements that capture interannual variability and vegetation dynamics.

Scale mismatch problems between model outputs and validation measurements represent a persistent challenge that can lead to apparently poor model performance even when the model is actually functioning correctly. A satellite-derived ET product with 1-kilometer resolution, for example, cannot be directly compared to a flux tower measurement that integrates over a 200-meter footprint, particularly in heterogeneous terrain. The Water and Energy Balance Monitoring (WEBM) network in the Netherlands has addressed this challenge by installing multiple flux towers within single satellite pixels, allowing researchers to quantify the sub-pixel variability that contributes to differences between point measurements and area averages. More sophisticated approaches use footprint models to determine what portion of each satellite pixel actually contributed to flux tower measurements, and source area models to estimate what fraction of the flux tower footprint is represented by each pixel. These techniques help reconcile scale differences but introduce additional uncertainty and require detailed information about atmospheric conditions and surface properties.

Model ensemble approaches have emerged as powerful tools for addressing model uncertainty and improving prediction reliability by combining outputs from multiple models rather than relying on a single modeling approach. The

## 1.12 Future Directions and Emerging Technologies

The sophisticated computational approaches and multi-scale validation frameworks we have developed to address the challenges in evapotranspiration modeling set the stage for a new era of innovation that promises to transform our understanding and application of this critical hydrological process. As we stand at the intersection of unprecedented computing power, revolutionary sensing technologies, and growing water management challenges, the field of evapotranspiration science is poised for breakthroughs that will make today's state-of-the-art approaches seem primitive in comparison. These advances will not merely incrementally improve our existing capabilities but will fundamentally reshape how we observe, understand, and manage evapotranspiration across scales from individual leaves to entire continents. The convergence of artificial intelligence, ubiquitous sensing, and high-resolution observation platforms is creating opportunities that were the realm of science fiction just a decade ago, promising to address some of the most pressing water challenges of the 21st century.

### 1.12.1 12.1 Machine Learning Integration

Machine learning integration represents perhaps the most transformative force reshaping evapotranspiration modeling, offering powerful new approaches to extract patterns from complex datasets and overcome limitations of traditional physics-based models. Deep learning applications have emerged as particularly promising for ET estimation, with convolutional neural networks demonstrating remarkable ability to learn the complex relationships between satellite observations and evapotranspiration rates without explicit programming of physical processes. Researchers at Stanford University have developed deep learning models that ingest multispectral satellite imagery, weather data, and topographic information to produce ET estimates with accuracy comparable to or exceeding traditional process-based models, but with dramatically reduced computational requirements. These models have proven particularly valuable in regions where the physics of evapotranspiration are poorly understood or where traditional models struggle due to data limitations, such as tropical mountain ecosystems where complex terrain creates microclimates that defy simple parameterization.

Hybrid physics-ML model approaches represent an exciting middle ground that combines the theoretical rigor of process-based models with the pattern recognition capabilities of machine learning, offering the best of both worlds for evapotranspiration estimation. The National Center for Atmospheric Research has pioneered hybrid approaches where machine learning algorithms learn to correct systematic biases in physics-based models, effectively creating ensemble systems that leverage the strengths of both methodologies. These hybrid models have shown particular promise for addressing the scale mismatch challenges discussed in the previous section, using machine learning to bridge the gap between point measurements and pixel-scale predictions. In the Colorado River Basin, hybrid models have improved ET estimates by 30-40% compared to either approach alone, providing water managers with more reliable information for allocation decisions. The elegance of these approaches lies in their ability to incorporate physical constraints while learning from observational data, ensuring that predictions remain physically plausible while capturing patterns that might be missed by purely theoretical approaches.

Pattern recognition in complex datasets has opened new frontiers in evapotranspiration science, allowing researchers to discover subtle relationships and feedbacks that were previously hidden in the complexity of environmental data. Machine learning algorithms applied to long-term flux tower records have revealed that certain combinations of temperature, vapor pressure deficit, and soil moisture conditions predict transpiration shutdown events days before they occur, offering potential for early warning of drought stress. Similarly, unsupervised learning techniques applied to satellite time series have identified distinct evapotranspiration regimes across different ecosystems, providing a new framework for understanding how vegetation responds to climate gradients. The Max Planck Institute for Biogeochemistry has used these approaches to classify global ET patterns into archetypal responses that differ in their sensitivity to climate variability, providing insights that could improve predictions of ecosystem responses to climate change. These pattern recognition capabilities become particularly valuable as we accumulate increasingly long and detailed observational records, creating opportunities to discover emergent properties of evapotranspiration systems that only become apparent at large scales.

Uncertainty quantification with ML methods addresses one of the most critical challenges in evapotranspiration modeling – understanding how confident we should be in model predictions – through sophisticated probabilistic approaches that go beyond traditional error analysis. Bayesian neural networks, for example, can provide not just point estimates of ET but also probability distributions that reflect the uncertainty in predictions based on the quality and quantity of input data. Researchers at Cornell University have developed ML systems that automatically detect when input conditions fall outside the range of training data and adjust uncertainty estimates accordingly, providing users with crucial information about when model predictions should be treated with caution. These uncertainty quantification approaches become particularly valuable for decision-making applications where the consequences of incorrect predictions vary widely, such as drought early warning systems where false alarms and missed events have very different costs. The integration of uncertainty quantification into operational ET modeling represents a crucial step toward more responsible and effective use of these tools in water management.

### **1.12.2 12.2 Internet of Things Applications**

The Internet of Things (IoT) is revolutionizing evapotranspiration monitoring by creating dense networks of interconnected sensors that provide unprecedented spatial and temporal coverage of environmental conditions. Distributed sensor networks are emerging as powerful complements to traditional weather stations and satellite observations, filling the critical gaps in coverage that have limited our ability to monitor ET at field and landscape scales. The University of California, Davis has deployed one of the world's most sophisticated IoT networks for agricultural water management, with over 10,000 wireless sensors monitoring soil moisture, temperature, and microclimate conditions across California's Central Valley. These networks provide real-time data that can be processed through ET models to generate field-scale water use maps updated hourly, enabling irrigation decisions that account for spatial variability within individual fields. The scalability of these systems is remarkable – costs have fallen to the point where commercial farmers can deploy sensor networks for just a few dollars per acre, making precision ET monitoring accessible even to

small-scale operations.

Real-time ET monitoring systems powered by IoT technologies are transforming water management from a reactive to a proactive discipline, providing the continuous information needed to optimize water use while preventing waste and crop stress. The smart irrigation controller market has exploded in recent years, with systems like Rachio and RainMachine integrating weather forecasts, soil moisture data, and ET calculations to automatically adjust irrigation schedules based on actual plant needs. These systems typically reduce water use by 20-40% compared to traditional time-based irrigation while maintaining or improving landscape health. More sophisticated implementations are emerging in agriculture, where IoT systems combine field sensors, drone observations, and satellite data to provide comprehensive ET monitoring across entire farming operations. The Australian company The Yield has developed such systems for specialty crops, using predictive analytics to forecast irrigation needs 24-48 hours in advance, allowing farmers to plan water deliveries and labor more efficiently. These real-time capabilities become increasingly valuable as water scarcity intensifies and the cost of water rises, making precise water management economically essential.

Edge computing for field applications addresses the connectivity and latency challenges that have limited IoT deployment in remote agricultural areas, where internet connectivity may be unreliable or nonexistent. By performing data processing and model calculations directly on IoT devices or local gateways rather than in the cloud, edge computing enables real-time ET monitoring even in disconnected environments. The University of Nebraska-Lincoln has developed edge computing solutions that run simplified ET models on low-power microcontrollers embedded in soil moisture sensors, providing local ET estimates that can trigger irrigation valves without requiring cloud connectivity. These approaches are particularly valuable for developing regions where internet infrastructure is limited but water management needs are acute. The Food and Agriculture Organization has piloted such systems in East Africa, where edge computing devices process weather station data to calculate reference ET for smallholder irrigation schemes, providing crucial information that would otherwise be unavailable. The democratization of ET modeling through edge computing represents a crucial step toward global water security.

Citizen science data integration opens new possibilities for expanding evapotranspiration monitoring beyond professional networks, leveraging the power of distributed observation to capture fine-scale patterns across vast areas. The GLOBE Program, an international science and education initiative, has engaged students and citizens in collecting weather data that can be used to validate and improve ET models, creating a global network of observation points that far exceeds professional monitoring capacity. More recently, smartphone applications have emerged that allow citizens to contribute observations of plant water status and soil conditions that can calibrate remote sensing ET estimates. The iNaturalist platform, while primarily focused on biodiversity, has inadvertently created a valuable record of vegetation phenology that researchers have used to improve the timing of seasonal ET cycles in models. These citizen science approaches not only expand data coverage but also create public engagement with water issues, building awareness and support for water conservation initiatives. As sensor technologies become increasingly accessible through smartphones and consumer devices, the potential for citizen science contributions to ET monitoring will only continue to grow.

### 1.12.3 12.3 High-Resolution Modeling

Sub-meter scale ET mapping represents the cutting edge of spatial resolution, revealing patterns of water use that were previously invisible to all but the most intensive field campaigns. The development of unmanned aerial vehicle (UAV) platforms equipped with thermal cameras and multispectral sensors has made it possible to map ET at the scale of individual plants or even leaves, opening new frontiers in precision agriculture and plant physiology research. Researchers at the University of Arizona have used UAV-based thermal imaging to map water stress in individual cotton plants within commercial fields, revealing surprising patterns of water use that vary with irrigation system design, soil variability, and even microtopography. These ultra-high-resolution maps have shown that water use can vary by 50% or more across distances of just a few meters, challenging the assumption of field-scale uniformity that underlies most irrigation management practices. The ability to detect these fine-scale patterns enables truly precision irrigation that applies water not just where it's needed but in the exact amounts required by each plant.

UAV-based thermal imaging has revolutionized ET monitoring by providing the surface temperature measurements essential for energy balance approaches at resolutions unattainable by satellite systems. While satellites like Landsat provide 30-meter thermal resolution, UAV platforms can achieve 5-10 centimeter resolution, sufficient to resolve temperature differences between sunlit and shaded leaves or between different parts of individual plants. The Swiss Federal Institute of Technology (ETH Zurich) has developed sophisticated UAV systems that combine thermal, multispectral, and LiDAR sensors to create comprehensive 3D maps of vegetation structure and temperature, enabling detailed analysis of how canopy architecture influences ET patterns. These systems have revealed that within-plant temperature variations can exceed 5°C, creating substantial gradients in transpiration rates that affect overall water use efficiency. The temporal flexibility of UAV systems is equally valuable – they can be deployed on demand to capture ET patterns during critical periods like heat waves or irrigation events, providing insights into plant responses that would be missed by the fixed overpass times of satellites.

LiDAR integration for structure represents a crucial advancement in high-resolution ET modeling, addressing the fundamental challenge that evapotranspiration depends not just on 2D surface properties but on the 3D arrangement of vegetation elements. Airborne LiDAR systems can map vegetation structure with centimeter-scale accuracy, providing detailed information about canopy height, density, and vertical foliage distribution that directly influences radiation interception and turbulent transfer. NASA's G-LiHT airborne imager has demonstrated how combining LiDAR structure with hyperspectral and thermal measurements enables sophisticated 3D modeling of ET within forest canopies, revealing how different canopy layers contribute differently to total water use. These approaches have shown that in tropical forests, the upper 20% of the canopy may account for over 50% of total transpiration due to greater light availability, while shaded leaves in the lower canopy contribute relatively little despite representing substantial leaf area. Understanding these 3D patterns is crucial for predicting how forests will respond to climate change and for developing accurate models of water and carbon cycling.

Urban canyon modeling advances address the unique challenges of estimating ET in complex urban environments where buildings create intricate patterns of shade, wind, and heat that vary at meter scales. Traditional

ET models struggle in these environments because the assumptions of homogeneous, extensive surfaces break down completely. Researchers at MIT have developed computational fluid dynamics models that explicitly resolve airflow and radiation patterns within urban canyons, providing the detailed environmental information needed for accurate ET estimation. These models have revealed that urban trees can experience ET rates up to 50% higher than rural trees due to the urban heat island effect, while simultaneously facing greater water stress due to limited soil volumes. The integration of these urban canyon models with high-resolution remote sensing data enables city-scale ET mapping that accounts for the complex interactions between buildings, pavement, vegetation, and atmosphere. This capability becomes increasingly valuable as cities worldwide invest in green infrastructure to mitigate heat islands and manage stormwater, requiring accurate understanding of how urban ET patterns influence local climate and water balance.

#### **1.12.4 12.4 Real-Time Prediction Systems**

Nowcasting applications for agriculture represent one of the most practical applications of real-time ET prediction, providing farmers with short-term forecasts of water needs that enable more efficient irrigation management. These systems combine weather forecasts, soil moisture observations, and ET models to predict crop water requirements hours to days in advance, allowing irrigation to be scheduled when it will be most effective. The University of Florida's Agricultural Weather Network has developed a nowcasting system that provides 48-hour forecasts of reference ET with 90% accuracy, enabling citrus growers to optimize irrigation timing around predicted rainfall events and avoid unnecessary applications. The economic impact of these systems can be substantial – studies have shown that farmers using ET nowcasting can reduce pumping costs by 15-20% while maintaining yields, primarily by avoiding irrigation immediately before rainfall and by applying water during cooler parts of the day when evaporative losses are lower. As weather forecasting continues to improve and ET models become more sophisticated, the lead time and accuracy of these nowcasting systems will only increase, creating new opportunities for precision water management.

Extreme event early warning systems leverage real-time ET monitoring and prediction to anticipate drought, heat stress, and other conditions that threaten agricultural productivity and ecosystem health. The U.S. Drought Early Warning System has incorporated real-time ET anomalies as leading indicators of developing drought conditions, often detecting water stress weeks before it becomes apparent in precipitation deficits or vegetation indices. These systems are particularly valuable for identifying “flash droughts” that develop rapidly under combinations of high temperature, low humidity, and precipitation deficits, catching farmers and water managers off guard. The European Drought Observatory has implemented similar systems that use ET measurements from the Copernicus Sentinel satellites to detect emerging water stress across the continent, providing early warning that enables proactive water management before severe impacts develop. The integration of these early warning capabilities with insurance products and disaster assistance programs represents a crucial step toward building resilience to climate variability and change.

Adaptive management systems represent the ultimate integration of real-time ET monitoring, prediction, and control, creating automated systems that can adjust water management in response to changing conditions without human intervention. The most sophisticated implementations are found in controlled environment



agriculture, where greenhouse computers continuously monitor ET rates and adjust irrigation, ventilation, and shading systems to maintain optimal growing conditions. These systems can reduce water use by 50-70% compared to conventional greenhouse management while improving crop quality and yield. More recently, similar adaptive systems have emerged for field agriculture, with automated center pivot systems that adjust irrigation rates in real-time based on variations in ET across the field. The Texas A&M AgriLife Center has developed such systems that use soil moisture sensors, weather stations, and ET models to implement variable rate irrigation that changes continuously as conditions evolve throughout the day. These adaptive systems represent a fundamental shift from pre-programmed to responsive water management, potentially revolutionizing agricultural water efficiency.

Decision support platforms integrate real-time ET information with economic models, crop simulations, and water availability forecasts to provide comprehensive guidance for water management decisions. The California Department of Water Resources' Integrated Regional Water Management platform combines ET forecasts with reservoir operations, water rights allocations, and economic impact models to help water managers make informed decisions during drought conditions. These systems enable scenario analysis that explores the consequences of different water allocation decisions, helping balance competing needs for agricultural, urban, and environmental water uses. Similar platforms are emerging for irrigation district management, where real-time ET estimates help optimize water deliveries across thousands of acres while maintaining equity among water users. The integration of ET science into these decision support tools represents a crucial step toward more sustainable and resilient water management, ensuring that scientific understanding directly informs policy and management decisions.

#### **1.12.5 12.5 Emerging Sensor Technologies**

Nanosensor applications promise to revolutionize evapotranspiration monitoring by enabling measurements at spatial and temporal scales that were previously impossible, potentially transforming our understanding of plant water relations at the most fundamental level. Researchers at Cornell University have developed plant-attached nanosensors that can measure transpiration rates, leaf water potential, and stomatal conductance continuously on individual leaves, providing insights into plant responses to environmental conditions with unprecedented resolution. These sensors, smaller than a grain of rice, can be attached to leaves without significantly affecting plant physiology, creating the possibility of networks of sensors that monitor water use throughout entire plant canopies. The applications extend beyond basic research to practical agriculture, where nanosensors could provide early detection of water stress before visible symptoms appear, enabling irrigation interventions that prevent yield losses. As manufacturing costs decline and sensor capabilities improve, these technologies could democratize plant-level monitoring, making detailed physiological measurements accessible beyond research laboratories.

Hyperspectral thermal imaging combines the temperature sensitivity of thermal remote sensing with the detailed spectral information of hyperspectral imaging, creating powerful new capabilities for evapotranspiration monitoring. Traditional thermal sensors measure total thermal radiation in broad wavelength bands, while hyperspectral thermal systems can distinguish radiation from hundreds of narrow spectral bands, pro-

viding information about surface emissivity and temperature simultaneously. The Jet Propulsion Laboratory has developed airborne hyperspectral thermal sensors that can separate temperature from emissivity effects with unprecedented accuracy, addressing one of the fundamental challenges in thermal remote sensing of ET. These systems have revealed subtle variations in surface properties that influence ET rates, such as changes in leaf water content that affect emissivity and thermal emission. The