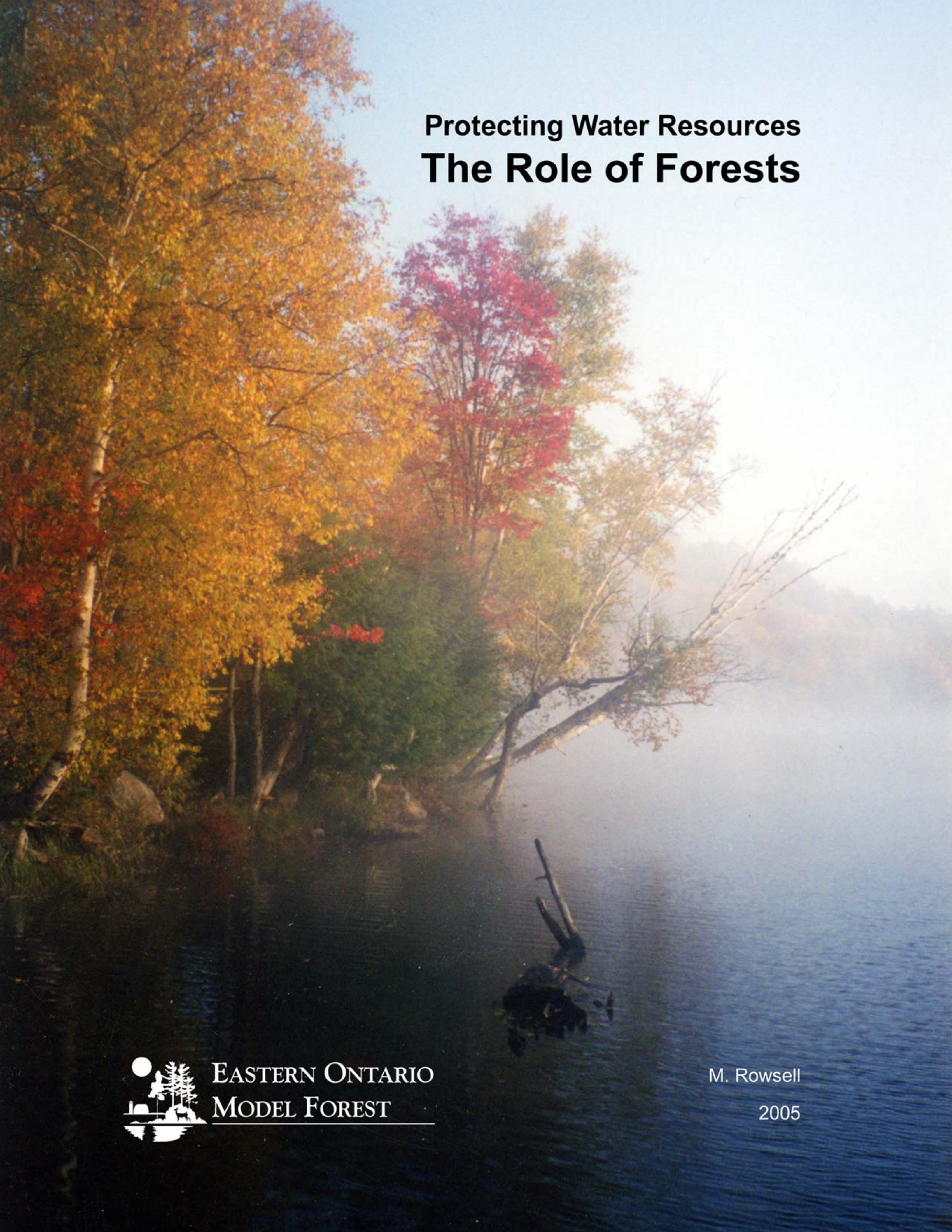

Protecting Water Resources
The Role of Forests

M. Rowsell

Eastern Ontario Model Forest

2005

“There are certain portions, certain sections of the earth's surface which, in the wise economy of nature, must always be maintained as forests, and that our watersheds must be maintained as forests. All the hills, mountains and plateaus which are the sources of flowing streams or rivers, should never be allowed for any consideration whatever, to remain anything else than forest.”

“I should like to impress upon every Canadian farmer the necessity of covering with trees every rocky hill and the bank of every running stream. It is very easily done. He has only to scatter the seeds on the ground, fence it and nature will do the rest.”

Prime Minister Wilfred Laurier
1st National Forest Congress
Ottawa, January 10-12, 1906

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PREFACE

There are over twelve thousand lakes, ponds, rivers, and reservoirs comprising over one thousand square kilometres of open water in eastern Ontario. Add to this close to nin thousand wetlands with approximately the same area. Eastern Ontario has an extensive natural and constructed drainage network with over twenty-one thousand kilometres of drains, ditches, creeks, and streams. Forest cover in eastern Ontario comprises thirty-four percent of the landscape. This value ranges between seventy-five percent in the highlands of Lanark to approximately twenty percent in the intensive agricultural lands in the east.

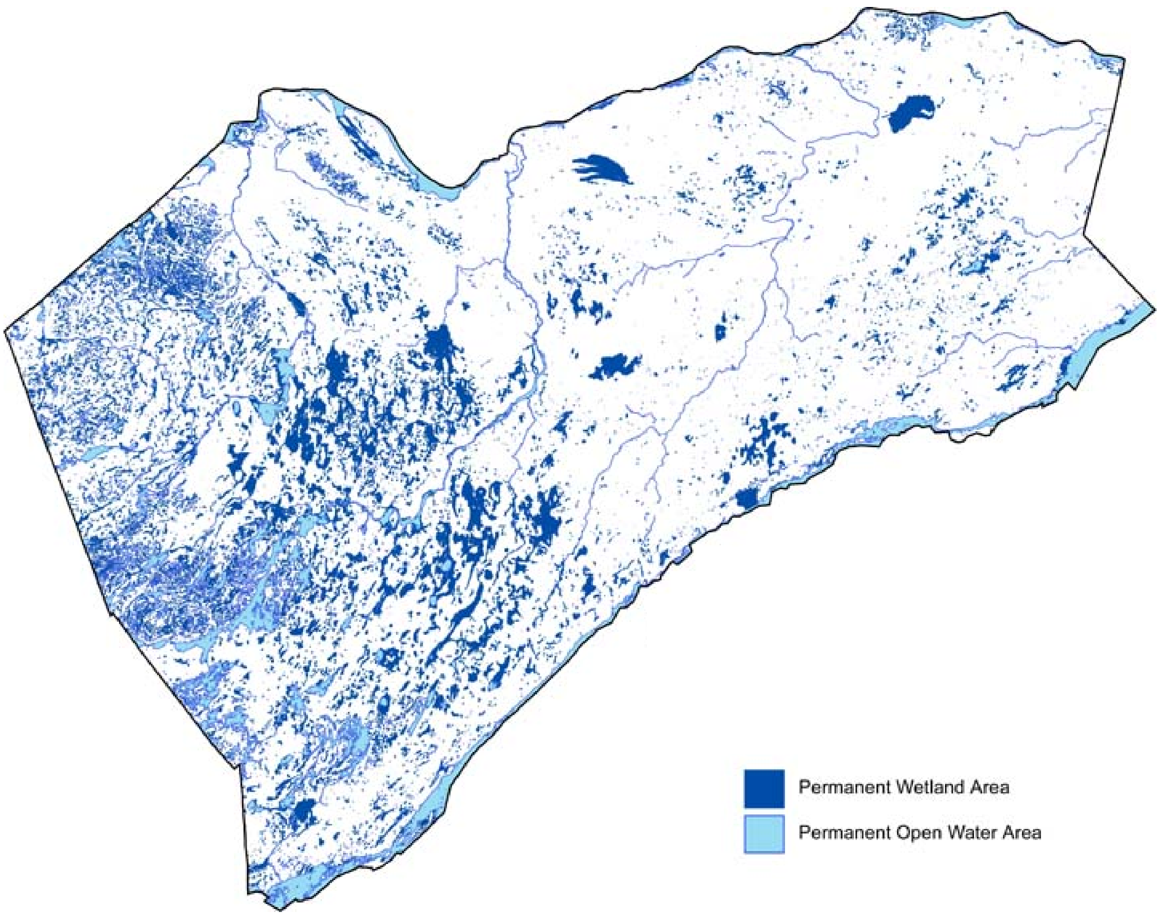


Figure 1: Major Surficial Hydrology in Eastern Ontario

Water and forests are very important resources providing food, energy, habitat, and other biological, chemical, physical, and socio-economic functions. Forests affect the occurrence, distribution, circulation and quality of water. Water is essential to life; plants and animals depend on water for growth, development, and survival.

A forest is a community dominated (typically greater than sixty percent canopy cover) by trees and woody vegetation that covers a large area. Thickets, savannas, woodlands, and plantations are other vegetated features that have varying tree cover in eastern Ontario.

There are many different types of forests in eastern Ontario. Distinguishing characteristics include: species composition, size, diversity, and density with variation depending mainly on temperature and precipitation. Forests provide a number of natural resources, and also perform a variety of environmental functions. Resources associated with forests include timber, water, soil, wildlife, and vegetation; all of which can be greatly affected by forest management activities. Environmental functions performed by forests include: control of water and wind erosion, protection of head water and reservoir areas of watershed and riparian zones, sand dune and stream bank stabilization, preservation of wildlife habitats and gene pools, mitigation of flood damage and wind speed, and sinks for atmospheric carbon dioxide (CO2).

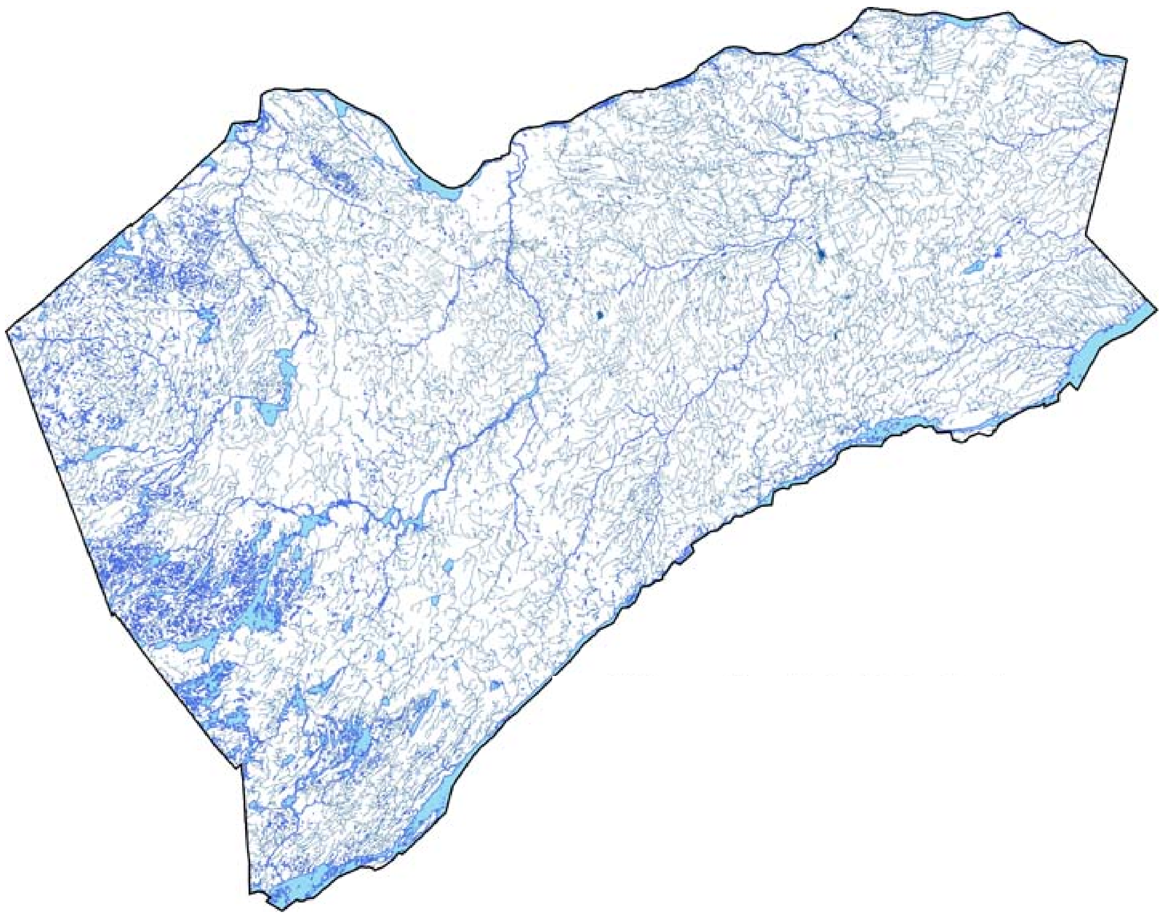


Figure 2: Minor Surficial Hydrology in Eastern Ontario

As populations increase, development and subsequent pressures on all natural resources also increase. This pressure places water and forest protection as two of the most important issues in the 21st century. Water and forests are not independent natural resources, they are symbiotic. This report discusses forest hydrology, the study of the interface between forest and water. An understanding of forest hydrology is fundamental to watershed management, maintaining land productivity and protecting water resources.

Globally, forest covers approximately 30 percent of the land, yet this percentage generates 60 percent of total runoff. In other words, most of our drinking water supplies originate from forested areas. Studies have shown that water flowing from forested watersheds is much cleaner than water coming from other lands, frequently meeting drinking water guidelines without treatment. Management activities in the forest impact forest canopies and forest floors. These may affect water quantity through their impacts on transpiration and canopy interception losses, infiltration rate, water holding capacity, and overland flow velocity. These activities can also affect water quality; for example, exposing mineral soils to direct raindrop impacts, the loss of soil binding effect from root systems, increasing overland flow, and accelerated decomposition of organic matter. All forests should be managed with their impacts on water resources in mind.

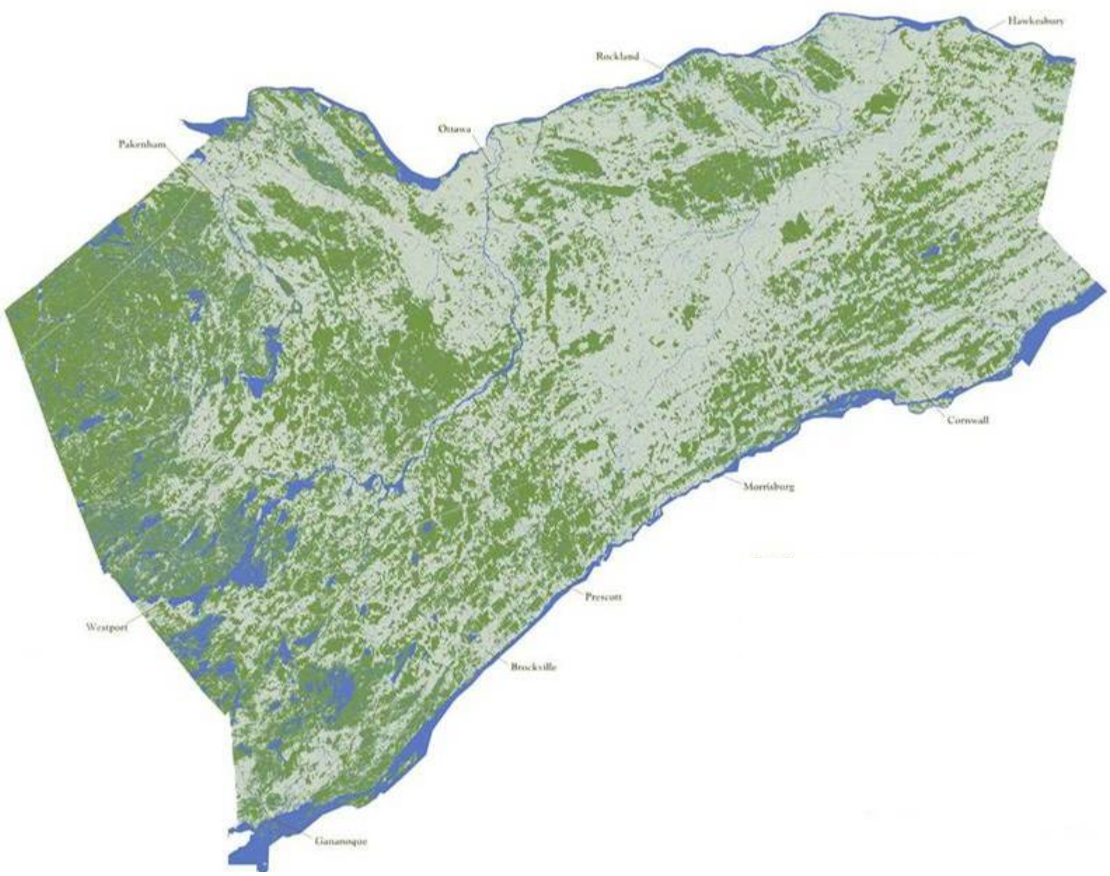


Figure 3: Forest Cover in Eastern Ontario

The purpose of this report is to summarize how forests impact water quantity and quality. There are two objectives: to summarize forest hydrology concepts, processes, and principles; and to discuss relationships between forests and various hydrologic processes. This report is designed to aid in identifying forest hydrology initiatives that should be undertaken in the Eastern Ontario Model Forest (http://www.eomf.on.ca). It will also serve to help identify soil and water indicators for state of the forest reporting (http://sof.eomf.on.ca).

This report is organized into two sections reflecting the two objectives stated above. Part I: Concepts, Processes, and Principles is designed to build a knowledge foundation for the reader to better understand the discussions in the following section, Part II: Relationships. The relationship section looks in detail at the relationship between different hydrologic processes and forests and draws straight forward conclusions.

PART I
CONCEPTS, PROCESSES, & PRINCIPLES

Introduction

Forest hydrology is the study of forests and their unique relationship to water in forested landscapes. The overall focus of forest hydrology is how forest vegetation and their associated soils, along with catchment topography, and climate all interact to govern the cycling of water through the forest and further downstream. Focus is on understanding how different forest vegetation types and stand conditions influence the hydrologic cycle. Themes studied under forest hydrology include interception of precipitation by forest vegetation, evaporation and transpiration from vegetation, and their relationships with streamflow. This report looks at each of these areas and draws conclusions regarding their effect on water quantity and quality.

In order to fully understand the relationships between forests, water, and soil (the key components of forest hydrology), it is important to understand the concepts, processes, and principles behind the themes. This section will discuss these in relative detail as is required to understand and appreciate the interconnections presented in Part II: Relationships. The following text is not intended to replace the overwhelming resources already produced regarding water and forest knowledge; instead it is a summary of the main concepts, processes, and principles necessary to set the foundation to facilitate the efficient transfer of forest-water relationships.

WATER FUNCTIONS

Water is extremely important; it performs many functions essential to life and the environment. For all intents and purposes, water functions can be categorized into four groups: biological, chemical, physical, and socioeconomic.
Biological Functions

Biological Functions

Life cannot exist without water; it is essential for survival, growth, and development. Fundamental plant processes such as nutrient absorption and photosynthesis require water. Up to seventy-five percent of a living tree's weight is either water or matter made from water (Chang, 2003). Water provides habitat for over ninety percent of the Earth's organisms. Oceans, rivers, lakes, streams, ponds, reservoirs, wetlands, and even puddles are home to life. Biologically, wetlands are some of the world's richest ecosystems. Riverine1, lacustrine2, and palustrine3 comprise the recognized wetland types in eastern Ontario. In terms of hydrologic mechanisms, wetlands contribute to aquifer recharge, flood control, sediment control, waste water treatment, biogeochemical cycling and storage, and water supply.

Lakes, ponds, and reservoirs are comprised of three life zones: littoral, limnetic, and profundal. Closest to shore and flooded with sunlight penetrating the floor, the littoral zone provides habitat to both flora and fauna. The limnetic zone is in the open water offshore where at least 1% of the light transmits through the aquatic horizon (compensation depth), fish and other aquatic organisms thrive. The profundal zone is reached when sunlight cannot penetrate through the water and respiration is greater than photosynthesis. This is habitat to scavengers and bacteria.

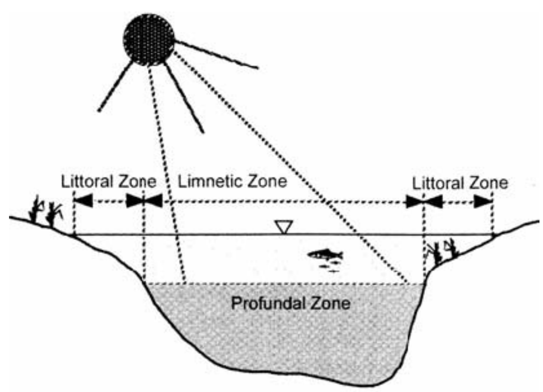


Figure 4: Open Water Body Zones

Water velocity largely determines habitat in a river, stream, or creek. Variations in water temperature, dissolved oxygen, nutrients, and light penetration all contribute to diversifying the environment. The aquatic-terrestrial interface commonly referred to as the riparian zone when vegetated plays a large role in regulating many of these processes (e.g. temperature).

[1] Adjacent to rivers and streams
[2] Of or relating to or living near lakes
[3] Nontidal wetlands dominated by trees, shrubs, or persistent emergent vegetation or small shallow wetlands

Chemical Functions

Water has the greatest ability over all other liquids to dissolve substances due to its chemical structure. A water molecule is comprised of one large oxygen atom and two smaller hydrogen atoms. Due to the arrangement of the hydrogen atoms (105° apart on one side of the oxygen atom) the water molecule has an electropositive (hydrogen) end and an electronegative (oxygen) end. This causes water molecules to be attracted to one another (cohesion). Chains and then sheets of water molecules form, thus creating viscous and tense surfaces. The same electric attraction causes water molecules to break down other substances (adhesion). This dissolving characteristic causes water to be the most powerful cleansing agent. Approximately

half of the known elements only exist while dissolved in water. Most chemical reactions occur in aqueous solutions. Water as a chemical reaction medium can alter the chemical properties of many materials, for example, the pH of a solution will change once water is added. Processes such as hydrolysis, hydration, and dissolution all occur through water. These processes ultimately degrade, alter, or synthesize materials through the use of water.

Physical Functions

The Earth's atmosphere is partly composed of water vapour which absorbs and reflects solar radiation from the sun. As an excellent energy storage medium, water stores heat when temperatures are high and releases it when temperatures are low (diurnal temperature flux). This ability is due to high thermal capacity and latent heat (described later). The frequency of precipitation is regulated by large bodies of surface water. When overlying air is cooler than the surface water temperature, water tends to migrate towards the cooler air thus causing instability in the air mass, resulting in rainfall.

Water, due to its fluid character is a good transport agent. Nutrients, sediment, seeds, chemicals, bacteria, insects, and pathogens are all examples of matter that water moves. Water in motion can also be very powerful. Soil erosion, nutrient loss, mass movement, and sedimentation are the main mechanisms through which liquid water can alter the physical environment. Weathering through freeze-thaw, abrasion, and hydrolysis4 are also common. Landscape formations such as valleys, floodplains, and gullies are a direct result of water's power and endurance. Landforms created as a result of glacial movements are particularly prevalent in eastern Ontario whether they are till deposits, eskers, or historic lakebeds.

Socio-economic Functions

Surface water holds vast potential to the recreational enthusiast. Canoeing on a calm lake, fishing off a dock, battling a whitewater hole, or skating down a canal are all disciplines that water and only water can provide. The subject of water inspires poets, painters, photographers, and musicians. Many religious activities centre on water as well, including baptising and holy cleansing. The civilized world has long since known the value of water. The majority of the populated centres are located adjacent to water. In many cases this is due to its transportation potential. These free highways are busy areas of trade and commerce. The buoyancy factor that water can afford allows huge quantities of merchandise to be moved. In eastern Ontario, the largest communities like Ottawa, Cornwall, and Brockville are on the Ottawa and St.

[4] Hydrolysis occurs when minerals react with water to form other products. Feldspar, the most common mineral in rocks on the earth's surface, reacts with water to form secondary minerals and additional ions that are dissolved in water.

Lawrence Rivers. Smaller communities such as Perth, Smiths Falls, Kemptville, Almonte, and Manotick were established on the banks of rivers to take advantage the water power to run sawmills and grist mills.

The lapping of a tide on a beach conjures up feelings of relaxation and comfort. The minerals and heat of water has long been used as therapy for aching muscles and other ailments. Spa and resort industries rely on the relaxing qualities of water and their environments. Farming (agriculture and aquiculture) is very reliant on water. Irrigation of crops yields produce in areas normally not fit to produce crops. Irrigation accounted for 33% of off-stream water consumption in the United States in 1995 (Chang, 2003). Hydroponics and fish culture also account for large uses of water. Industry uses water as a cooling agent, lubricant, solvent, cleansing agent, and reagent.

WATER PROPERTIES

Many of the characteristics that water exhibits are used as standards to measure other substances. Water will be discussed in terms of physical, hydraulic, chemical, and biological properties.

Physical Properties

Water can occur in nature in three states (or phases). Below freezing (0°C) water is a solid (ice or snowflakes), between freezing and boiling (100°C) water is a liquid, and above its boiling point water is a gas or vapour. Water changing from solid to liquid is said to be melting. When it changes from liquid to gas it is evaporating. Water changing from gas to liquid is called condensation. Frost formation is when water changes from gas directly to solid form. When water changes directly from solid to gas the process is called sublimation.

Most liquids contract in volume when they get colder. Water is different, it contracts until it reaches 4°C, then it expands until it is solid. This explains why solid water (ice) is less dense that liquid water; as a result ice floats on liquid water. In changing from one phase to another, water either absorbs or releases energy (heat) into the surrounding medium. This hidden energy is commonly referred to as latent heat. The four basic types of latent heat are: latent heat of condensation, latent heat of fusion, latent heat of sublimation, and latent heat of vapourization. Latent heat of condensation refers to the heat gained by the air when water vapor changes into a liquid. Latent heat of fusion refers to the heat lost or gained by the air when liquid water changes to or from ice. Latent heat of sublimation refers to the heat lost or gained by the air when ice changes to and from vapour. Latent heat of vapourization refers to the heat lost by the air when liquid water changes into vapour. This is also commonly known as the latent heat of evaporation.

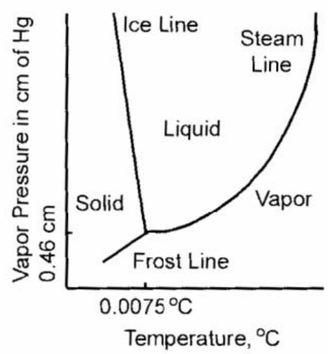


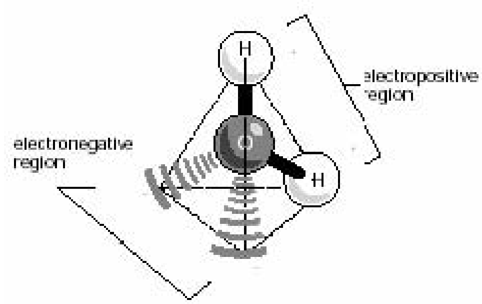
Figure 5: The Physical States of Water

When air reaches its capacity to hold vapour, a pressure called the saturation vapour pressure is exerted. If the water vapour present is less than this maximum then the air is capable of taking up more moisture. The ratio of actual pressure to the saturation vapour pressure at any given temperature, expressed as a percentage, is called the relative humidity. When a piece of wet wood is exposed to air which is not already saturated (i.e. its relative humidity is less than 100%), evaporation takes place from the surface of the wood. The rate of evaporation is dependent on the difference between the vapor pressure exerted by the wet wood surfaces and that of the air/water vapor mixture in immediate contact with them. This principle is very important when understanding the evaporation of accumulated precipitation from the surface of vegetation because the humidity plays a large role in water loss. Diffusion is defined as the spontaneous spreading of one substance through another (Radel, 1990). Water vapour will diffuse through air in response to a gradient in density or pressure. Diffusion always occurs towards lower densities or pressures.

It is important to distinguish between heat and temperature. These terms are important when discussing the effect solar radiation has on evaporation. Heat is a form of energy; it can be quantified to represent the total kinetic energy of the molecules that comprise the material. Temperature is a measure of hot versus cold. It represents the average amount of kinetic energy per molecule a material possesses. The heat (or energy) required to raise the temperature of 1 gram of any substance by 1 degree Celsius is called the specific heat, and is measured in calories. The specific heat of water is 1 cal/°Cg-1. Heat capacity builds upon the principle of specific heat; the heat capacity of a substance is the total heat contained within as determined by the mass, temperature, and specific heat.

Chemical Properties

Figure 6: A Water Molecule



Two atoms, connected by a covalent bond, may exert different attractions for the electrons of the bond. In such cases the bond is polar, with one end slightly negatively charged (-) and the other slightly positively charged (+). Although a water molecule has an overall neutral charge (having the same number of electrons and protons), the electrons are asymmetrically distributed, which makes the molecule polar. The oxygen nucleus draws electrons away from the hydrogen nuclei, leaving these nuclei with a small net positive charge. The excess of electron density on the oxygen atom creates weakly negative regions at the other two corners of an imaginary tetrahedron. Because they are polarized, two adjacent water molecules can form a linkage known as a hydrogen bond. Hydrogen bonds have only about 1/20 the strength of a covalent bond. Hydrogen bonds are strongest when three atoms lie in a straight line (i.e. O-H-O). Water molecules join together to form a hydrogen-bonded lattice. The cohesive nature of water is responsible for many of its unusual properties, such as high surface tension, specific heat, and heat of vaporization.

Substances that dissolve readily in water are termed hydrophilic. They are composed of ions or polar molecules that attract water molecules through electrical charge effects. Water molecules surround each ion or polar molecule on the surface of a solid substance and carry it into solution. Ionic substances such as sodium chloride dissolve because water molecules are attracted to the positive (Na+) or negative (Cl-) charge of each ion. Polar substances such as urea dissolve because their molecules form hydrogen bonds with the surrounding water molecules.

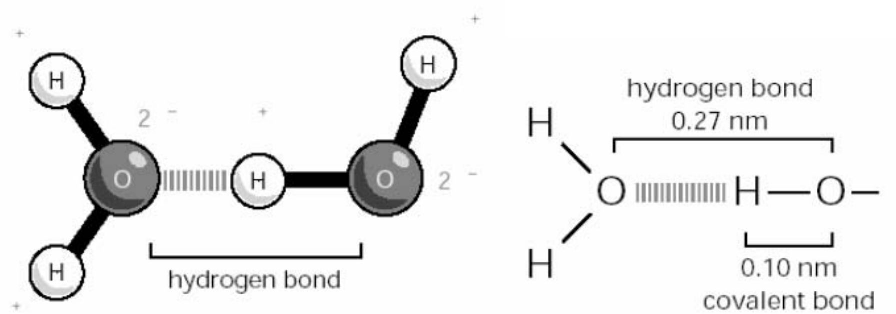


Figure 7: Hydrogen Bond

Molecules that contain non-polar bonds are usually insoluble in water and are termed hydrophobic. This is especially true of hydrocarbons, which contain many C–H bonds. Water molecules are not attracted to such molecules and so have little tendency to surround them and carry them into solution.

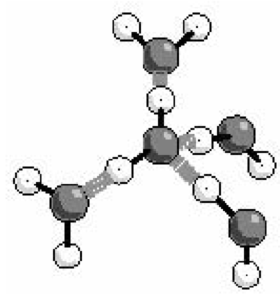


Figure 8:
Hydrogen Bonded Lattice

Hydraulic Properties

Hydraulic properties deal with the behaviour of water in hydrostatic (no motion), and hydrokinetic (motion) states and with the forces involved in motion (hydrodynamics).

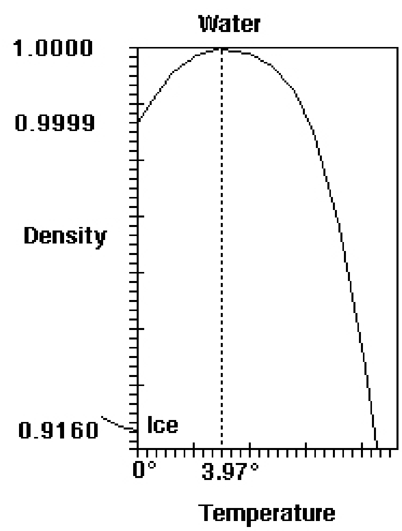
Density

Density is defined as the amount of mass per unit volume. The density of water changes with temperature and state (solid, liquid, gas). The density decreases with increased temperature. In frozen water, individual water molecules are all present at the maximum distance from adjacent molecules due to hydrogen bonding. Hence, water exhibits its minimum density when it is in the form of ice; this is why ice floats. The transformation of ice to water is accompanied by the breaking of some of the hydrogen bonds, leading to a dramatic increase in density.

Water Pressure

Pressure is defined as weight per unit area. Weight is a function of mass relative to the vertical force of gravity. Water pressure is determined by the vertical height of the water column, not volume or shape of the container because of its relationship to unit area. The pressure resulting from the weight of water is called hydrostatic pressure. The pressure within a container is equal in all directions because liquids take the shape of the container. Also, a force applied in one area of a closed container can result in a greater force in another area. This effect is used in hydraulics to create a mechanical advantage (e.g. hydraulic brakes).

Figure 9: Density of Water as a Function of Temperature



Buoyancy

Since an object immersed in a fluid displaces the same volume of fluid as the volume of the object, it is possible to determine the precise volume of the object by immersing it in water. Extending this idea further, if the mass of the water displaced is greater than the mass of the object, the object will float (Note: this calculation will require that the object be forcibly submerged). If the mass of the water is less than the mass of the object, the object will sink. If by chance the two masses are equal, the object will be suspended in the water at varying depths depending on the initial depth of the object and the water's temperature and turbidity.

Cohesion and Adhesion

Water molecules are attracted to other water molecules. This is called cohesion. Water molecules can also be attracted to other materials. This is called adhesion. As noted earlier, the oxygen end of water has a negative charge and the hydrogen end has a positive charge. The hydrogen's of one water molecule are attracted to the oxygen from other water molecules. This attractive force is what gives water its cohesive and adhesive properties. This is important when understanding canopy drip and overland flow through forest ecosystems.

Surface Tension

Surface tension is a measure of the strength of the water's surface. The attraction between the water molecules creates a strong film, which among other common liquids is only surpassed by that of mercury. This surface tension permits water to hold up substances heavier and denser than it self. A steel needle carefully placed on the surface of a glass of water will float. Some aquatic insects such as the water strider rely on surface tension to walk on water. While surface tension is a result of cohesive properties, capillary action is related to the adhesive properties of water. Water molecules are attracted to other types of molecules. When one water molecule moves closer to another type of molecule the other water molecules (which are cohesively attracted to that water molecule) also move. Capillary action is limited by gravity. Plants take advantage of capillary action to pull water from the soil. From the roots water is drawn through the plant by another force, called transpiration.

Viscosity

Absolute viscosity is the characteristic of a fluid which causes it to resist flow. Water has a relatively low viscosity, therefore it flows very easily. Maple syrup is a more viscous fluid which offers a far greater resistance to flow. The viscosity of a fluid causes a loss in pressure as it flows, so that an increase in viscosity requires an increased amount of energy to pump fluid at the same rate. Expressed another way, flow from a constant pressure source will decrease as the viscosity of the flowing fluid increases. The viscosity of a liquid is highly temperature dependent. An increase in temperature will cause a decrease in viscosity.

Biological Properties

Temperature

Temperature is a measure of how cold or hot a substance is. Temperature is the main factor controlling state changes in water. Water freezes at 0°C and boils at 100°C. Water temperature in the natural environment (streams, lakes, etc.) is primarily affected by solar radiation; however, precipitation, inflow, atmospheric radiation, and heat from the ground (conduction) affect the temperature to lesser degrees. Decreasing the cover characteristics of a stream will thus result in increased water temperatures due to increased solar radiation.
Cooler water regulates biological activities in the aquatic environment, thus improving water quality. Cold water has higher concentrations of dissolved oxygen, lower rates of microbial activity, lower decomposition of organic matter, and generally fewer or slower chemical reactions. Warmer temperatures increase biological oxygen demand (BOD), which is the chemical oxidation of dissolved, suspended, or deposited organic materials and the subsequent decomposition of these materials by aquatic micro organisms.

Dissolved Oxygen

Dissolved oxygen, (DO), is defined as the amount of oxygen dissolved in water and is usually expressed in mg/L. Oxygen from the atmosphere dissolves in water at the interface between water and air water through a process called diffusion. The solubility of oxygen in water is inversely proportional to water temperature and increases with increasing atmospheric pressure (Figure 7).

The concentration of dissolved oxygen in a water body is determined by three factors: oxygen holding capacity, rate of oxygen depletion, and the rate of oxygen replenishment. The ability of water to hold oxygen is primarily a function of temperature and existing concentration due to the principle of diffusion. The rate of oxygen depletion is primarily a function of respiration rates of aquatic plants and decomposition rates of organic material by aquatic organisms (generally measured using biological oxygen demand (BOD). Oxygen replenishment is achieved through photosynthesis of aquatic plants and the dissolution of oxygen from the atmosphere. The rate of diffusion of oxygen at the water/air interface is primarily a function of the turbulence at the surface. Higher aeration rates are achieved at surfaces that are more turbulent.

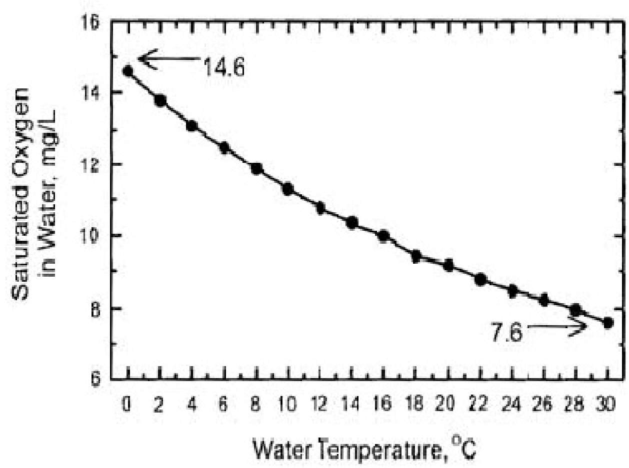


Figure 10: Dissolved Oxygen Vs. Temperature

pH

Water is comprised of hydrogen ions (H+) and hydroxyl ions (OH-). The pH of a solution is a measure of the concentration of hydrogen ions. Technically, it is the negative logarithm of the concentration of H+ ions. If the concentration of H+ ions is greater that the concentration of OH- ions the solution is said to be acidic, conversely, if the respective concentrations are opposite, the solution is termed basic. When concentrations of hydrogen ions and hydroxyl ions are equal the solution is neutral. The pH is measured using a scale from 1 (most acidic) to 14 (most basic), with 7 representing neutrality. Surface waters with low pH (acidic) can often be associated with organic acids resulting from decaying vegetation. High pH values (basic) can often be measured in surface water when underlying soils are calcium based like limestone.

Electric Conductivity

Electric conductivity (EC) is the ability of a substance to conduct an electric current. It is the opposite of resistance. The electric conductivity of water is proportional to the concentration of dissolved ions (e.g. dissolved salts) and water temperature. Increases in dissolved ion concentration will increase the ability of water to conduct electricity. Electric current flow increases with temperature. Conductivity is an important indicator of the chemical and physical conditions of the water. An inverse relationship exists between conductivity and the variables flow, precipitation, and turbidity. Water that is slowly transmitted to the stream (baseflow or groundwater flow) has more opportunities to pick up dissolved ions through weathering and other chemical reactions. Water that is quickly transformed from precipitation to runoff (surface run-off) tends to have fewer dissolved ions, thus causing a corresponding decline in conductivity at high discharges. Soil texture, salinity, and organic content are also related to electric conductivity.

Sediment

Sediments in water bodies are defined as particles, usually inorganic, that have been released into the water from the land surface. Sediment can be transferred from land to water through many mechanisms including: precipitation, gravity, overland flow, animals, and wind. Sediment can be in suspension, bouncing along the stream bed (siltation), or rolling along the stream bed (bed-load). The concentration of sediment is affected by geology, soils, topography, climate, vegetation cover, and land use activities. Turbidity is a common measure of sediment concentration. It is an optical measure which quantifies the clarity of water. This measure is dependent upon the size, shape, configuration, and colour of the sediment. High measures of turbidity can increase the odour, taste, temperature, solar absorption and the abrasiveness of water. These changes can lower water quality, water quantity and jeopardize the health of aquatic life.

Sediment yield or sediment load are terms that reflect loss of sediment at a watershed scale. These measures are usually determined by relating water flow to water volume and sediment weight. Generally watershed area has a negative effect on sediment loss. A smaller watershed will generally have higher sediment loss due to lower watershed storage, greater rainfall intensity, and steeper average slope. Sediment can act as a carrier for other elements and compounds that can then interact in water. This characteristic can affect water chemistry and water quality. Common elements or compounds can include pesticides, herbicides, air pollution fallout, and organic material.

WATER DISTRIBUTION

Hydrologic Cycle

The hydrologic cycle is a continuous process by which water is transported from the oceans to the atmosphere, to the land and back to the sea. This global cycling process involves many sub cycles. The global cycle is driven by the sun's energy. The quality of water changes throughout the cycle, however, the quantity of water on the Earth is finite. The global water cycle can be viewed as a closed system; however, regional sub cycles are often considered to be open to adjacent sub cycles. The hydrologic cycle (at any scale) is comprised of several components as shown in the diagram below.

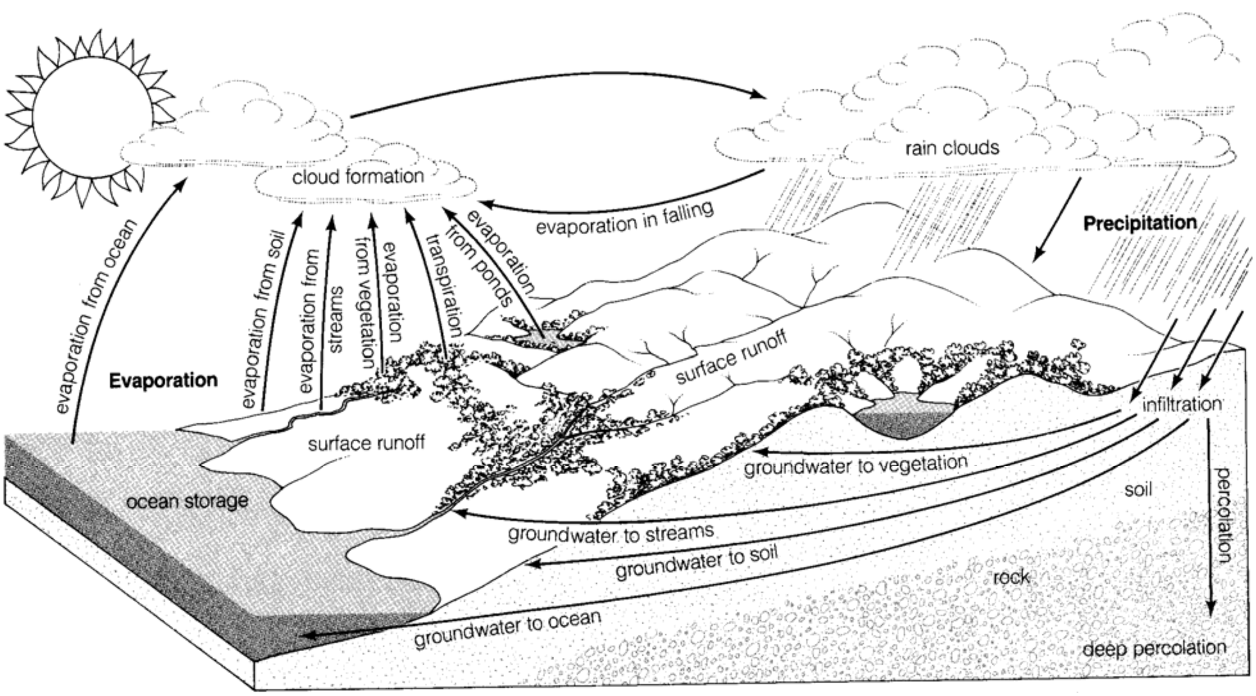


Figure 11: The hydrologic cycle

The hydrological cycle provides useful introductory concepts and permits the relationship between precipitation and stream flow to be expressed in a very general way. However this general view does not mimic reality for a specific area. For most hydrological purposes, river basins or watersheds are examined. In natural conditions most rivers and streams receive water only from their topographic drainage basin or watershed/catchment area. Each basin can be regarded as an individual system.

Drainage basin hydrological processes rarely operate completely uninfluenced by human activity. It is important to recognize that humans do modify the landscape and as such, modify every component of the hydrologic cycle. These impacts include large-scale modifications of channel flow or storage through activities such as afforestation, deforestation, and urbanization; the widespread development of irrigation and land drainage; and finally, large-scale removal of groundwater and surface water for domestic and industrial uses. Hydrological processes can be examined at three different scales: microscale (how water travels through soil), mesoscale (how water travels through catchment area), and macroscale (large-scale forest clearance or desertification). This report discusses results at the mesoscale. This scale is referenced by the terms watershed, catchment, and basin.

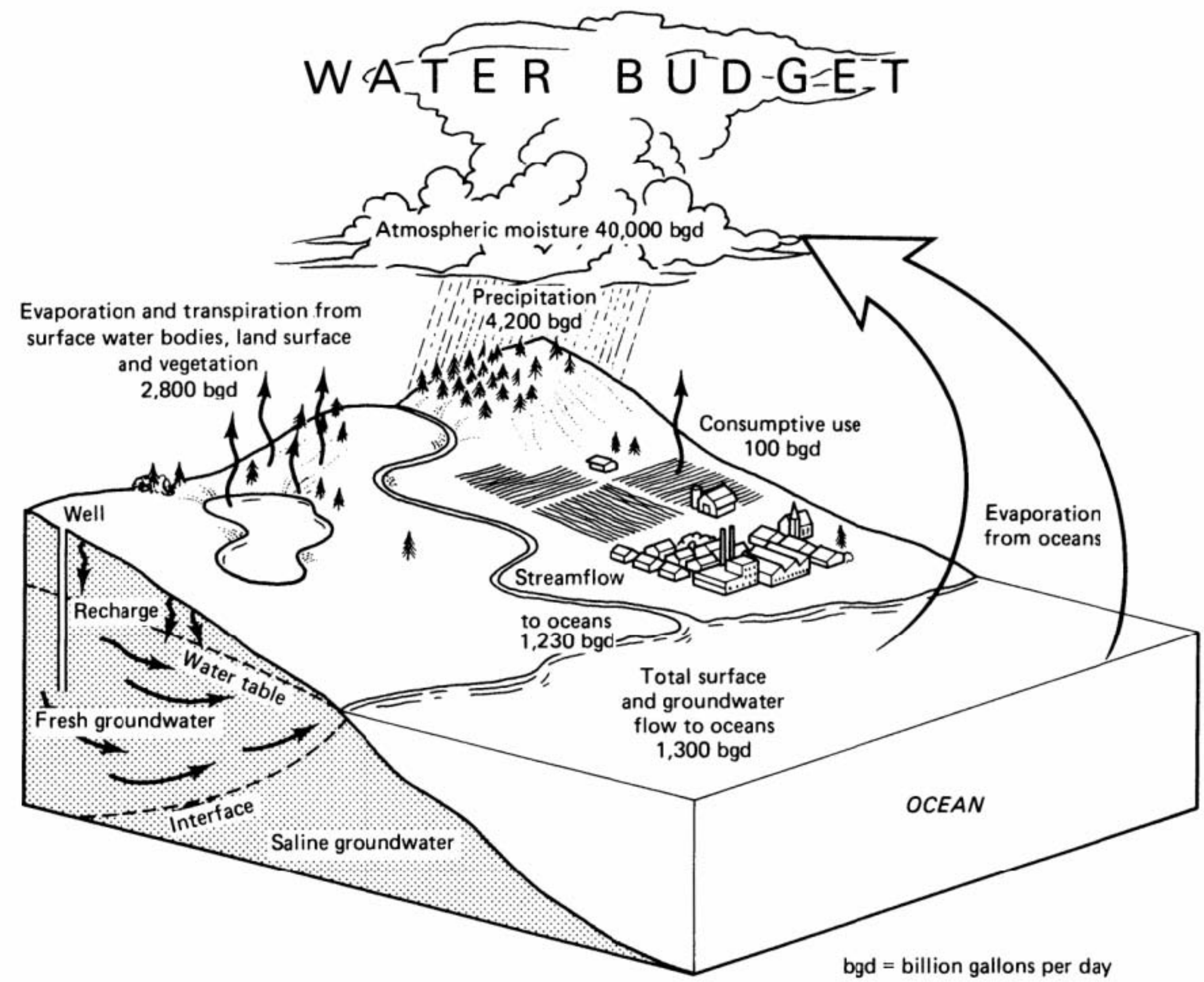
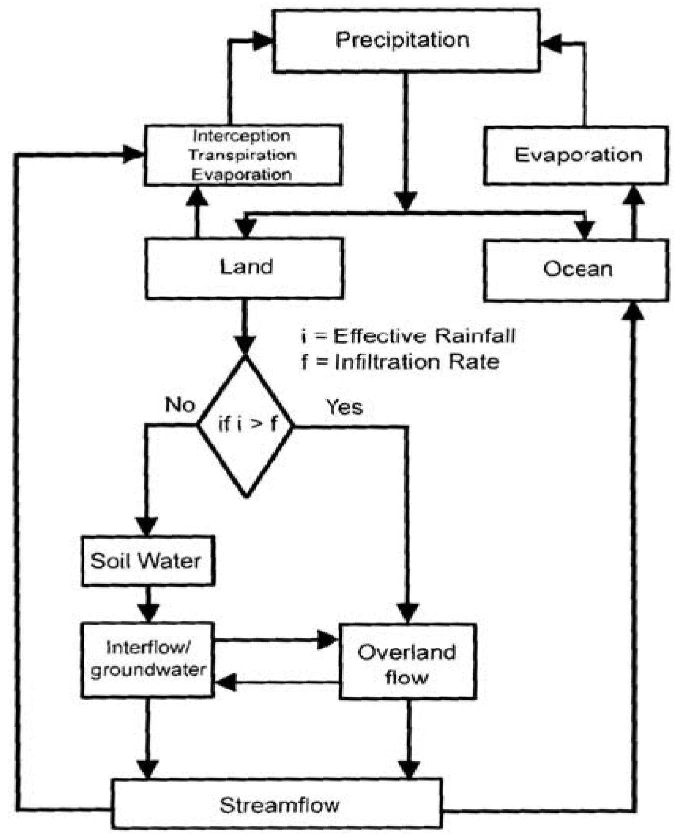


Figure 12: Hydrologic Budget for the coterminous United States (Viseman, 1989)

Hydrologic Budget

The components of the hydrologic cycle can be measured and thus accounted for in a hydrologic budget. The principle components of the hydrologic cycle are precipitation, transpiration, evaporation, surface runoff, groundwater flow, and infiltration. The hydrologic budget for both surface and subsurface processes can be reduced to:

Figure 13: Flow Diagram of the Hydrologic Budget (Ward, 1990)



$P – R – G – E – T = \Delta S$,

Where, P is precipitation, R is surface runoff, G is groundwater flow, E is evaporation, T is Transpiration, and ΔS is total available water. Each of these

Precipitation

Precipitation, such as rain, snow, sleet and hail, is a primary source of water needed to replenish watersheds. Precipitation is caused by the cooling of a rising air mass; it begins as water vapour in the atmosphere and then condenses into a liquid or a solid. The condensed air is then pulled towards the ground by gravity in the form of tiny droplets. Prior to reaching the ground, rain and snow can be intercepted by vegetation and ground litter. The retained water can be vapourised back into the atmosphere or eventually drip or infiltrate into the ground. The process of precipitation interception can affect a number of factors including soil moisture and the force with which the precipitation falls to the ground.

Runoff

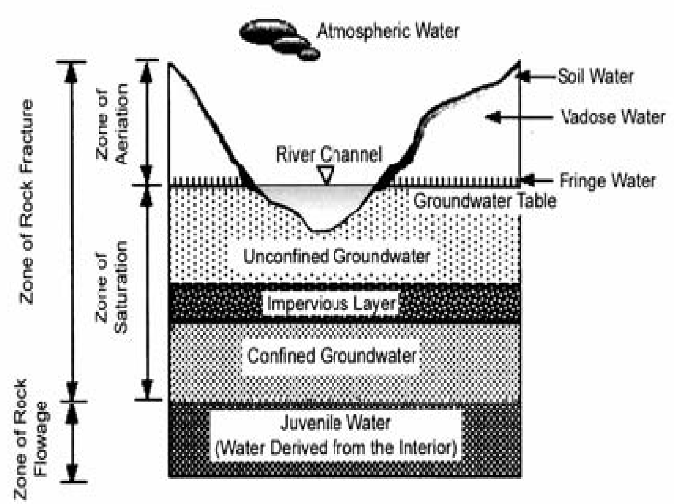
Once precipitation falls to the ground it can be absorbed or it can remain on the surface as runoff. When the amount of precipitation exceeds either the infiltration rate of the ground, or the water-holding capacity of the soil, surface runoff will take place. A number of factors can be responsible for surface runoff. These include climate, topography, soil, vegetation, human activity, and stream flow quantity and quality. Surface runoff also requires translocation, water storage area and the ability of water to change state.

Infiltration

Infiltration refers to the entry of water into the ground. Gravity, capillary attraction, and hydrostatic pressure, caused by the ponding (or pooling) of water promote infiltration. The rate of infiltration slows progressively with time as the soil pores continue to fill with water. Infiltration is much greater in a forest than on unvegetated ground. Infiltration generally depends on flow characteristics as well as certain surface and subsurface conditions. Surface conditions include: vegetation, land management techniques, surface temperature, slope, chemicals, surface flow velocity, and the ability of water to enter the soil. The subsurface conditions that can affect infiltration include: soil texture and structure, organic matter content, depth, pore space, layering, water content, groundwater table, and the root system.

Groundwater

Figure 14: Groundwater Zones



The term groundwater reflects all water under ground. There are two distinct zones within groundwater: zone of aeration and zone of saturation. In the zone of aeration both water and air exist in porous soils. As a rough estimate, approximately 25% of any given soil volume is water in this zone. The zone of saturation is composed of porous ground (sand, gravel, bedrock) saturated with water. The boundary between these two zones is the groundwater table. The very wet zone directly above the groundwater table is called the capillary fringe. This region is characterized by the upward migration of water due to capillary forces between soil particles. The region within the unsaturated zone that plant roots reach is called soil water. The area between soil water and the groundwater table is known as the vadose zone or gravitational water. This zone is characterized by the force of gravity is too great for plants to take advantage of the water resources.

Evaporation

Evaporation is the change in state of water from a liquid to water vapour. The transfer of energy towards water increases the kinetic energy, hydrogen bonds are broken and water vapour is diffused from higher to lower vapour pressure (i.e. from the evaporating surface into the surrounding air). The difference between the vapour pressures is known as vapour pressure deficit. The energy required for evaporation is known as the latent heat of vapourization. Solar energy is the major source of energy and control on evaporation, and thus distributions of solar radiation and evaporation tend to be strongly correlated. Another source of latent heat is the sensible heat of air, soil and rock. Also, the kinetic energy of the water is a source of latent heat that can fuel the evaporation process. Air temperature is a very important controlling factor of evaporation. It governs the capacity of air to hold water vapour, known as the saturation vapour pressure. It increases with increasing air temperature. The vapour pressure deficit is the difference between the saturation vapour pressure and the actual vapour pressure; this is the amount of additional water vapour that air can hold at a given temperature. Humidity also plays a role in evaporation rates; with constant air temperature (i.e., constant saturation vapour pressure), an increase in actual vapour pressure causes a decrease in the in the rate of evaporation, as the vapour pressure deficit is reduced and relative humidity rises. Increases in wind increase evaporation rates. Wind causes eddy (turbulent diffusion) and thereby maintains the vapour pressure gradient between air and the evaporating surface. The amount of turbulence is function of wind speed and surface roughness; the latter factor is negligible over calm water, but significant over a forest canopy. Evaporation can rise dramatically with increasing turbulence but only up to a critical limit determined by humidity, temperature and especially energy.

Evaporation and Transpiration

Vaporization from a wet soil surface is similar to that of a water surface. Soil moisture content decreases as evaporation occurs. The reduced soil moisture causes evaporation to fall below the potential rate. During the following drying stage, the evaporation rate is primarily determined by the water flow properties within soil, called hydraulic conductivity. The vapour flux is bigger in soils with high diffusivity, high vapour pressure, and a finer texture. The vapour flux is less in soils with deeper drying layers. Soil vapour diffusivities are affected by soil moisture content, temperature, and pressure. Mulches can be used for minimizing soil evaporation, but they are only effective during the early drying stages.

In plants water loss is linked to photosynthesis. Plants use a small amount of water directly in photosynthesis, but lose a large amount through the stomates during the uptake of carbon. The internal surfaces of leaf cells are covered with a thin coating of water, thus the air inside the leave tends to be saturated at the leaf temperature. The atmosphere is usually not saturated and thus the vapour pressure deficit between the interior of the leaf and the bulk atmosphere drives water loss from the leaf whenever the stomata are open. Pure evaporative water loss occurs only where vegetation is absent: ice and snow fields, bare soil and rock surfaces, and open water; otherwise water loss from land consists of evaporation from soil, evaporation of intercepted water, and transpiration of water by plants.

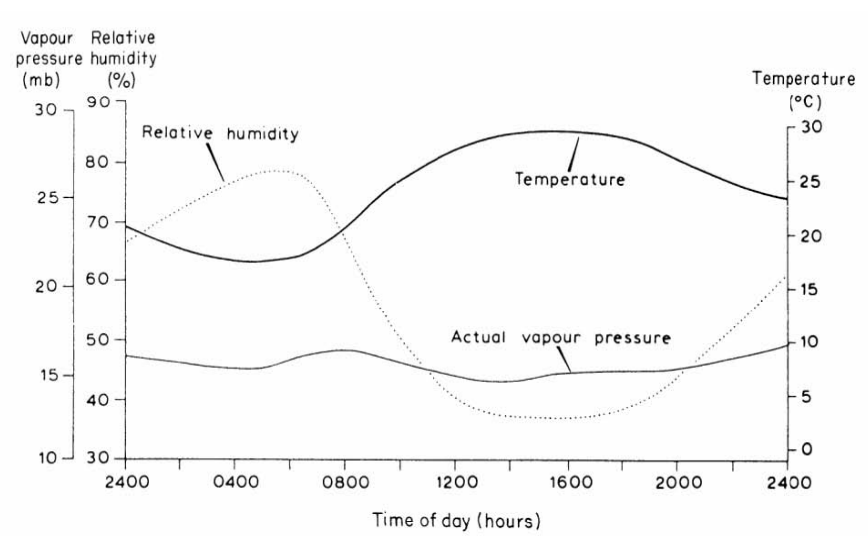


Figure 15: Diurnal variation in vapour pressure, relative humidity, and temperature

During transpiration, water is absorbed by the roots, it rises by capillary action to stomatal cavities in the leaves where it evaporates and is diffused through stomata. Transpiration maintains the turgor of non-woody plants; it delivers mineral nutrients to plant tissue and is also a cooling mechanism. The vapour pressure gradient between the leaf tissue (and bark, to a lesser extent) and the surrounding air draws water from soil into the roots and up the plant through the xylem. Under dry, windy and/or hot, sunny conditions, transpiration can exceed the rate at which water can be supplied from the soil; closing of the stomates prevents water loss but also access to atmospheric CO_2 for photosynthesis. Plants can control transpiration to some degree. Leaf area and leaf angle has evolved to maximize photosythesis under water limitations. Plants can control stomatal openings; they can adjust their osmotic potential (the amount of solutes in the plant liquids) which can control rates of water loss. Soil water storage is used by plants during times when actual evapotranspiration is greater than rainfall. The rate of transpiration loss is governed by both extrinsic and intrinsic factors. For example, transpiration loss from most plants will be large when the atmosphere is relatively dry. In most plants, leaf stomata open under daylight conditions and close at night, thereby introducing a clear diurnal variation in transpiration losses. Should the plant be unable to withdraw adequate water through its roots to match transpiration loss, internal stresses are setup. In response to this there may be a partial or complete closing of the stomata in order to limit transpiration.

FORESTS

Forests are biotic areas comprised primarily of trees and woody vegetation supporting a number of species of flora and fauna. Currently, forests cover one third of eastern Ontario. Forests are the home of countless plants, animals, insects, birds and fish. The many natural resources found within a forest ecosystem result from its specific microclimate. The plentitude of natural resources found within forests are used to support a number of industries based on vegetation, wildlife, soil, tourism and lumber.

General Characteristics

Trees found in forests are considered seed vascular plants. A seed vascular plant is perennial, stands upright, is woody, photosynthetic and is capable of living in a broad range of places. There are 3 common components to trees: the root system, the stem, and the canopy.

The root system is found at the base of the tree within the ground. An estimated 10% of the wood mass of a given tree can be found in the root system. The roots are responsible for the stability of the tree as well as pulling water and nutrients from the soil into the tree. Stems are the connecting agent between the root system and the canopy and generally account for more than 80% of the biomass of the tree. Stems can act as a mechanical disruption to wind and water movement. The canopy is a term that refers to the collective formation of branches, leaves, needles, etc. provided by the tops of trees. It is within the canopy that the majority of oxygen and carbon dioxide is exchanged and water is transpired as part of photosynthesis.

Broad Functions

Forests affect both the quantity and quality of water. The amount of water that is able to reach the soil is affected by the amount of canopy interception. The water that does reach the soil is pulled in to the root system to later be transpired from the tree. The root system and the amount of organic matter in the soil influence the infiltration rate and water holding capacity of the soil. The combination of these processes leads to a decrease in surface runoff. With less surface runoff, increased shade provided by the canopy, and increased soil stability resulting from the root system, neighbouring streams have cooler temperatures, lower concentrations of dissolved elements, and higher dissolved oxygen content.

The height, canopy, density, size, and depth of a forest exert an influence over any water and energy exchange. A forest can cause net radiation to be greater and temperatures to be lower in summer and higher in winter. The amount of incoming solar radiation is usually more at the canopy than on bare ground as a result of the colour and texture of the foliage and its ability to attract the sun’s rays. However, the long wave radiation being emitted from the ground into the atmosphere is reduced because of the canopy and the low wind movement. Canopy interception is another influential factor on the local climate. Canopy interception reduces the amount of precipitation reaching the ground and postpones snowmelt.

A mechanical function of forests is their effect on both water and wind erosion. Soil water erosion is controlled through a number of processes including reduced surface runoff resulting from both canopy interception and leaf litter, and increased soil porosity resulting from root systems. These functions greatly reduce soil erosion compared to bare ground. Wind can erode by removing and transporting soil particles. Both the rate of removal and transportation capacity is reduced in forest environments due to their affect on wind velocity. The degree to which a forest can reduce wind speeds depends on different factors, including: the direction of the wind, the density and height of the canopy, distance from the windbreak, and height above the ground. The presence of a forest or shelterbelt is the best permanent means of keeping wind erosion to a minimum.

Forest ecosystems function as habitat for flora and fauna species. Forests are a vital part of the biosphere; large-scale disruptions or alterations to a forest ecosystem can destroy its symbiotic state of equilibrium leading to biological disasters. Many of the species on the endangered species list are there as a result of a loss of forest habitat.

In terms of direct human health, forests play an important role. Plants are used for food, as well as medicine. Plants are either directly or indirectly responsible for between 25 and 50% of all of the prescription drugs used in the U.S. today (Chang, 2003). Forests are used as areas for releasing tension. Many popular recreational activities take place in forests. Forests, both urban and rural, have attributes that lead to increased mental and physical health. The forest has the ability to replenish oxygen, diminish noise, and reduce dust, which all have positive effects on people’s physical health. Educational opportunities are also plentiful in forested areas. Students can learn about ecological processes, wildlife habitats, and nature conservation.

SOILS

Soil is the foundation material upon which all terrestrial life and much aquatic life exists. It is the medium within which vegetation roots; it is a reservoir for nutrients and water. It is the site of decomposition of organic material and the launching point for minerals to the nutrient cycle. Soil is a natural product formed from weathered rock by the action of climate and living organisms. There is a close relationship between soil and vegetation. Often one can infer soil types based on overlying vegetation. Roots comprise a large proportion of soil. The soil provides stability upon which to anchor their stem and canopy. Soils also provide plants with the nutrients and water necessary for photosynthesis. Vegetation influences the development of soil, affects its chemical and physical properties, and contributes to the organic matter content.

Soil Development

Soil is created through a process called weathering. Weathering can be broken down into physical, biological, or chemical. Physical weathering involves rock surfaces flaking and peeling as a result of being exposed to the combined action of water, wind, and temperature. Water can seep into cracks and freeze, the resultant expansion causes the rock to crack. This physical weathering process is called freeze-thaw. Eventually, weathered material will be transported (via wind, water, gravity etc.) away from the source. This exposes unweathered rock to these natural processes. The unconsolidated material below the soil from which soil is developed is called the regolith. Biological weathering is caused by plants, soil organisms, and animals. Plants further breakdown the regolith with their roots. Roots facilitate further physical weathering by allowing water to percolate into soils. Plants cycle nutrients from the soil by absorbing nutrients through roots and ultimately returning organic matter as litter. Soil organic matter is broken down to humus through decomposition. This is achieved through soil organisms (worms, grasshoppers, etc.) consuming the matter and excreting partially decomposed waste. This is then attacked by micro organisms, bacteria, and fungi which reduce the matter to compounds like carbohydrates, proteins, and fats. Through a process called mineralization, these compounds are reduced to simple products like carbon dioxide, water, minerals, and salts. Soil can also be weathered through chemical processes. Water is the solution necessary for chemical reactions to occur. Precipitation then promotes chemical weathering. Elements such as calcium, potassium, sodium, soluble salts and carbonates are washed deep into the soil where they react with acids and gases.

Soil Profile

Most soils have a number of distinctive horizontal layers called soil horizons. Each horizon has a different thickness, colour, texture, and composition. A cross-sectional view of the various horizons is called a soil profile. A majority of mature soils have around three or four of the six major horizons. The six horizons are named O, A, E, B, C, and R. The top layer, O, is made of leaf litter and partially decomposed organic debris. The A-horizon is found below the O-horizon and is a porous mixture of humus and mineral particles also known as the topsoil. The A-horizon varies in thickness anywhere from 1cm on steep slopes to over a metre on flat grassland. This horizon is also the most fertile in the soil profile. Below this layer is the E-horizon. If there is no A-horizon, this layer will form directly underneath the O-horizon. Water percolates down through the E-horizon dissolving organic and inorganic and carrying it down to the B-horizon. The B-horizon, also known as the subsoil, usually contains an accumulation of iron, aluminum, humic compounds and clay. This section provides water and oxygen to deeprooted plants. In the C-horizon there is a zone of relatively un-decomposed mineral and rock particles. Sometimes, this layer contains the same material that has slowly weathered to form the minerals in a soil's horizons. There is no organic material in this layer. Finally, the bottom of the soil profile is characterized by bedrock, or the R-horizon. The R-horizon varies in its distance from the surface. Some places have exposed bedrock and other places have a few feet of soil over top. Generally, the R-horizon does not appear in soil profiles.

Soil Characteristics

Soil chemistry plays an important role in controlling the availability of nutrients in the soil for plant uptake. Chemical elements in the soil have several fates; they can be absorbed in soil particles, dissolved in soil water, or included in mineral and organic matter. Ions can move from soil to plants, through animals and be returned to the soil. In aquatic environments, the ions are dissolved and create dilute solutions. In terrestrial environments, ions are less mobile because they are held by soil particles of clay and humus. The availability of nutrients is governed by the makeup of the soil, specifically the proportion of clay versus humus. Soil is composed of particles called micelles; these plate-like particles have negatively charged edges and sides which attract positively charged ions, water, and organic substances. The ability of a soil particle to absorb positively charged ions is called cation exchange capacity. Soil types vary in their cation exchange capacity based on the structures of clays and the amount of organic content. Soils with high organic content have up to four times the cation exchange capacity of inorganic soils (based on weight) (Smith, 1992). Soil fertility and nutrient availability is greater in soils with higher cation exchange capacity. Ions are taken up by plants when in soil solution. As plants remove ions from soil solution, other ions diffuse from soil particles into solution available for root uptake. Soils with greater cation exchange capacity will be able to provide more ions to plants. Acidity is a well known soil condition. Soils typically range between pH 3 (acidic) and pH 8 (basic). Soil acidity also affects the availability of nutrients. As soil acidity increases, the proportion of aluminum ions increases, and calcium, potassium, sodium and other nutrients decreases. Such increases in acidity cause nutrient deprivation and aluminum toxicity.

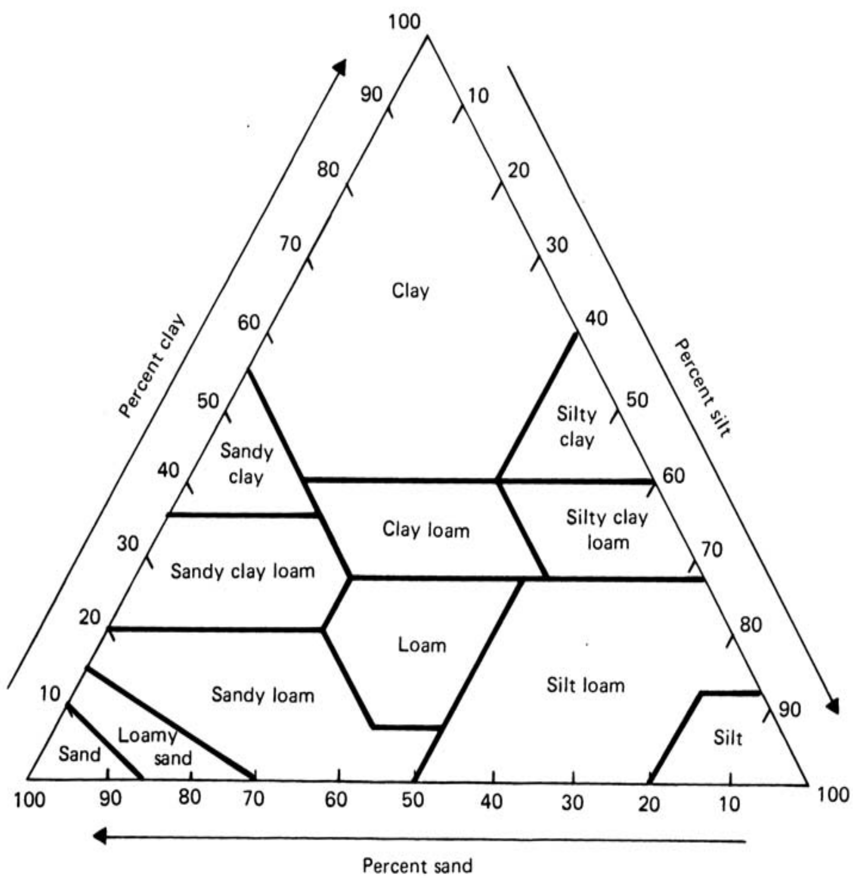


Figure 16: Soil Texture Classes (Smith, 1992)

Soil texture and structure are the primary characteristics that determine differences among soils. Texture is defined as the proportion of different sized soil particles; it is categorized into classes. Soil texture is a result of the type of parent material and the weathering processes it experienced. Soil is categorized into proportions of gravel, sand, silt, and clay. The clay component controls the most important properties of soil, including plasticity and ion exchange between soil particles and water. Soil particles are held together in clusters called aggregates or peds. Soil structure describes the arrangement of these peds. Terms such as granular, platelike, and columnar are used to describe soil structure. Aggregates tend get larger with soil depth; this is primarily a result of lower weathering activity.

Water percolates through soil via its pore space. Several conditions can occur under soil wetting. Under typical situations, soil pores are filled by gas and water. If the soil pores are not completely filled with water, the soil is said to unsaturated; it could accept more water. If the soil pores are filled with water and there is excess water available for runoff, the soil is saturated. If the same conditions apply but there is no excess water, field capacity has been achieved. Field capacity is the amount of water a soil can hold after water has drained under gravity. Different soils have different field capacities; it is primarily governed by texture because the water is being held by capillary forces between soil particles. Finer textured soils have stronger capillary forces, and therefore hold more capillary water. Water is lost from soil through evaporation and plant uptake. The wilting point is realized when the remaining soil water is adhered to soil particles in a thin film (hydroscopic water). Wilting point, as the name implies represents the soil moisture point where plants cannot use the water. Some fine textured soils can be 25% water at their wilting point. As inferred above, soil water and soil air are very important to plant growth. Too much water and anaerobic conditions can occur, too little water and wilting will result.

Soil Erosion

Soil erosion refers to the movement of soil particles to new locations by a number of forces (such as water or wind, etc). Erosion is a natural geological occurrence where the loss of soil is continuous and occurs at a normal rate. Accelerated erosion on the other hand can be very destructive if surface conditions are further disturbed by human activities. In order for erosion to take place, three steps must be taken: detachment, transport, and deposition.

The detachment of soil particles requires quite a bit of energy to overcome the cohesive forces of the soil. In water erosion, the forces that dominate the detachment of soil particles include striking raindrops and overland flow. Over time, freezing and thawing also have a great ability to increase detachment. With water expanding as it freezes, it exerts a pressure on the rock, mineral, or soil aggregate facilitating disintegration. The shear strength of a soil is the combination of cohesion, internal friction, and organic colloids that hold together the soil particles. Soil detachability refers to the soil's ability to withstand the forces of raindrop impact and surface flow. Soil detachability generally decreases with increasing organic matter content and infiltration rate and increases with increasing particle size.

In order for detached particles to become deposited in a stream, they must be carried by an agent to a new location. Both rainfall and runoff can act as these transporting agents. Rainfall transport takes place mainly through splash action. The splash capacity can be calculated as a function of the amount and intensity of the rainfall, the slope gradient, soil characteristics, wind speed and micro relief. Generally, the percent of total splashed soil that moves downhill is equal to the percent slope plus 50 (Ekern, 1953). Runoff carries soil particles in overland flow.

The transport capacity is the maximum amount of sediment that overland flow is able to move. The transport capacity of an agent depends on its energy level. This energy level is a function of its flow velocity, mass, slope gradient, hydraulic radius, and surface roughness. Due to the fact that the velocity of overland flow increases with depth, the transport capacity is greater with depth.

The sediment yield is the amount of soil particles that are transported from a source to a certain point downstream. As a result of sediment yield impacts on reservoir capacity, water quality, aquatic life, stream habitat, channel morphology, flood stage, and riparian zones, estimates of sediment yield are crucial. Sediment that is transported down the stream is carried by suspension, saltation, or bedload movement. Suspension refers to the sediment being transported without making any contact with the stream bed. Saltation occurs when the sediment bounces along the streambed. Bedload movement refers to sediment rolling along the streambed. The size of the particles, transported as either suspended load or bedload, depends on both the hydraulic characteristics of the stream and the nature of the load. The term wash load refers to fine particles such as the silts and clays that are washed from banks into the stream during runoff. The wash load travels at basically the same speed as the water and will remain suspended in the stream water.

Deposition depends on the magnitude of the transport capacity and the size of the sediment load. If the transport capacity is greater than the sediment load, the sediment will continue to be transported. Deposition occurs only when the sediment load exceeds the transport capacity. During deposition, the larger, heavier round particles deposit first while the smaller, lighter platy particles remain suspended for longer. The larger particles are therefore deposited further upstream while the lighter, platy particles are deposited downstream.

PART II
RELATIONSHIPS

FORESTS AND PRECIPITATION

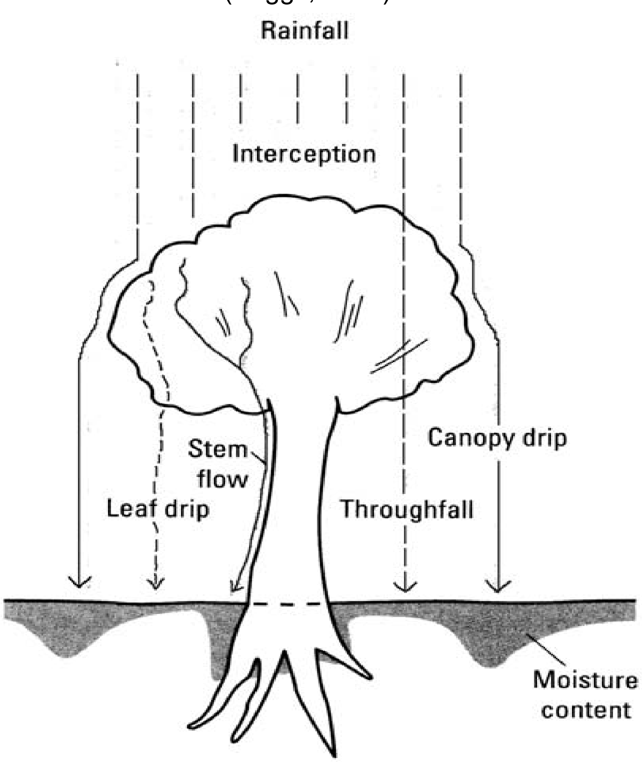
Precipitation is the primary input into a watershed's hydrologic budget. The quantity, quality, and timing of precipitation are all critical to the growth and health of forests. As an example, receiving a normal amount of rainfall in a given year may be of little value if it occurs in a few heavy storm events compared to a number of smaller rainfall events throughout the growing season. Likewise, extremes in precipitation amounts, whether too little or too much, can stress trees, weakening them and reduce their resistance to insects and diseases (Ohio Department of Natural Resources, 2003).

Forest canopies have mechanical effects on a number of processes that include: reducing wind speed in the forest, trapping suspended particles and dust, redistributing the energy budget at the ground, and slowing the velocity of raindrops.

Forests Intercept Precipitation

Trees act as a barrier against precipitation[5] reaching the soil. Interception can trap up to forty percent of incoming rainfall (Cumming, 2003). Precipitation has several fates once entering a forest. It could pass directly through the canopy and land directly on bare soil. It may be intercepted by the canopy and be detained there long enough to evaporate; or, it could drip from the canopy. Typically, 10-20% of the precipitation that falls during the growing season is intercepted and returned to the hydrologic cycles by evaporation (Viessman, 1989).

Figure 17: The Various Fates of Precipitation in a forest (Briggs, 1993)



Canopy interception is a negative component of the hydrologic budget due to its loss to the atmosphere through evaporation. In some cases the precipitation may collect in the canopy and then run down the tree stems and/or trunk; this is called stemflow. This water is directed to the root ball of the tree. Some precipitation will reach the litter layer (mulch covering the soil surface); it can be detained long enough to evaporate or pass through the litter and reach the soil surface; potentially on its way to roots. Once precipitation reaches the soil surface, the process of interception is complete and the process of infiltration begins. The litter layer is extremely important to both interception and infiltration. A conifer plantation has a much different litter layer (and understory) than a hardwood stand.

[5] The majority of the discussion in this section involves the interception of liquid precipitation (i.e. rain).

Total forest interception is generally regarded as the sum of canopy interception and litter interception. The precipitation that actually reaches the soil is called effective precipitation. Forest interception is an important event in the hydrologic cycle because of its effects on rainfall deposition, soil moisture distribution, snow accumulation and snowmelt, wind movement, heat dissipation and impact energy of raindrops on soil erosion (particle detachment).

Interception serves two roles in a watershed. First, the process is an important part of the water balance; it can result in either a loss or gain of water. The interception of precipitation by the forest canopy represents a major component of the influence forests exert on the water cycle. In the case of closed-canopy stands it may account for as much as 35% of mean annual precipitation (Chang, 2003). Second, interception plays an important role in protecting the mineral soil surface from the energy of rainfall.

Reduction of raindrop energy by interception minimizes soil detachment and subsequent erosion and also protects soil structure and infiltration capacity by reducing compactive forces. Litter that accumulates on the forest floor and understory plants absorb the physical impact of torrential downpours and releases the water gently to the mineral soil beneath. This cushioning action largely prevents the water from suspending large quantities of surface soil particles and thus clogging soil pores beneath (Wadsworth, 2003). There are two factors that affect interception: vegetation characteristics and meteorological characteristics.

Vegetative Characteristics Affect Interception

Following a dry spell, interception loss is usually highest at the beginning of a storm and then it decreases with time. The single most important factor is the storage capability of the vegetation cover (i.e. the ability of vegetation to collect and retain fallen precipitation). The interception storage capacity is at maximum when all leaves, twigs, and stems are dry. This is the point at which a very large percent of precipitation will not contact the ground. There is a limit to the amount of water (or snow) which the canopy and litter in a catchment can hold. Interception increases exponentially during a storm until the interception capacity is achieved and the weight of more rain overcomes the surface tension between the retained water and the tree. When interception capacity is reached, any additional input of precipitation becomes runoff, soil moisture, streamflow, or ground water. No extra water can be added until some is removed by evaporation. Evaporation takes place both during and after a storm. Even during periods of rainfall, a considerable amount of water can be lost by evaporation from the leaf surface.

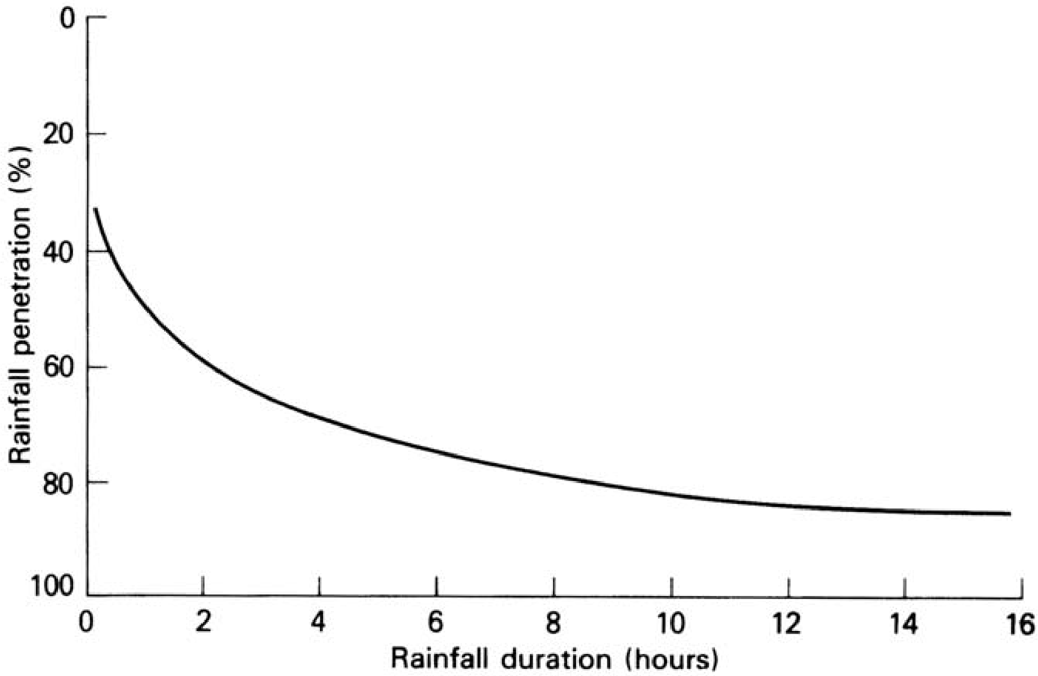


Figure 18: Relationship between the amount of rainfall reaching the forest floor and rainfall duration (Ward, 1990)

The amount of precipitation that actually reaches the ground surface is highly dependent on the nature and density of the vegetative cover. Water losses by interception are most pronounced under dense, closed canopy forest stands. In certain cases, vegetation can intercept moisture in the air which would not otherwise have fallen as precipitation. In this case, the main hydrological interest lies in the amount of water that is transmitted to the ground via throughfall and stemflow.

In terms of vegetative characteristics, interception capacity is a function of the vegetation type, plant density, plant structure, and plant community structure (University of Natal, 2003). Interception losses are greater from trees than grasses or agricultural crops. The primary reason is the larger evaporation rate from trees under wet conditions due to greater aerodynamic roughness (Ward, 1990). Coniferous trees intercept 25-35% of annual precipitation while deciduous trees intercept 15-25% despite leaf density (not to be confused with surface area) being greater in deciduous. Conifers have greater surface area than deciduous trees. However, during the growing season interception rates are comparable between coniferous and deciduous trees. For comparison a wheat crop intercepts 11-19% of precipitation during the growing season.

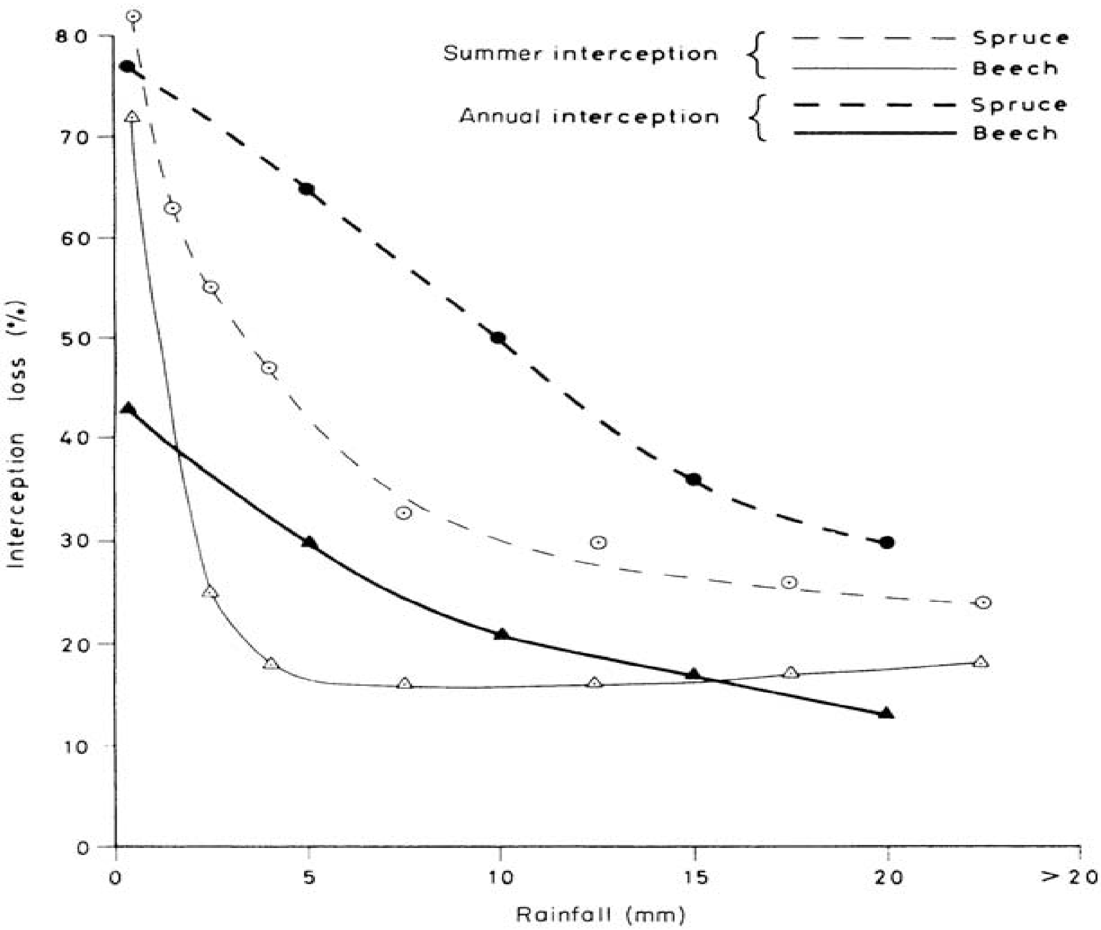


Figure 19: Interception losses from spruce and beech forests. (Ward, 1990)

Conifer interception is believed (Geiger, 1957) to be higher because water droplets cling to individual needles while water drops combine (cohesion) in deciduous leaves and drip from the leaf edge. Also, the open texture of coniferous needles allows greater circulation of air and consequently more rapid drying of the needle surface. This drying (evaporation) allows more water to be intercepted. Plant density is an important component of interception. Ground cover extent and canopy closure are good measures of plant density (better than biomass – mass/unit area). Greater plant density results in larger volumes of interception.

Plant structure is another factor of interception; specifically the number, size, flexibility, strength and pattern of branches; and the texture, surface area and orientation of leaves. Tree heights, diameters and volumes are a poor indication of interception capacity since they don't convey tree structure. The quantity of leaves varies among tree species and forest type. The quantity of leaves is often expressed in terms of the leaf area index (LAI) which is the ratio of total surface area of vegetation to the covered areas.

Generally, evergreen conifer species have the greatest leaf area index followed by deciduous hardwood, shrubs, and grasses. Therefore the interception capacity of trees will also follow this pattern. The interception capacity ranges between 0.3 – 6.6 mm for conifers, from 0.03 - 2.0 mm for hardwoods, from 0.3 – 2.0 mm for shrubs, and from 1.0 – 1.5 mm for grasses. LAI is a commonly used index for interception. Based on the fact that the surface area of a tree increases with age, the interception loss increases with the maturity of tree species.

Measuring date[a]	Weekly average precipitation catch (in. of equivalent rain)			Percent interception by forest cover	
	Spruce-fir	Birch	Pasture	Spruce-fir	Birch
11/9/65	0.24	0.33	0.39	38	15
11/16/65	1.01	1.25	1.45	30	14
11/23/65	1.01	1.23	1.36	26	10
12/10/65[b]	1.41	1.65	1.79	21	8
12/17/65	0.55	0.81	0.87	37	7
12/30/65	0.66	0.95	1.08	39	12
1/4/66	0.20	0.25	0.26	23	4
1/12/66	0.36	0.55	0.61	41	10
1/18/66	Trace	Trace	Trace	—	—
1/25/66	0.25	0.58	0.59	58	2
2/1/66	1.38	1.91	1.96	30	3
2/8/66	0.05	0.07	0.06	17	16
2/11/66	0.29[c]	0.02	Trace	—	—
2/15/66	0.76	0.81	0.98	22	17
2/21/66	0.17	0.22	0.22	23	0
3/2/66	0.86	1.23	1.45	41	16
3/7/66	0.76	0.84	0.97	22	13
3/15/66	0	0	0	—	—
3/29/66	0.73	1.13	1.27	43	11
Total	10.69	13.83	15.31	30.2	9.5

[a] The period between measuring dates is 7 days, except when precipitation occurred on the seventh day. In this event, measurement was postponed until precipitation ceased.

[b] Measurements were delayed until a method was devised to melt frozen precipitation on the site.

[c] This measurement in the spruce stand was the result of foliage drip during a thaw from previously intercepted snow.

Source: After C. E. Schomaker, "The Effect of Forest and Pasture on the Disposition of Precipitation," *Maine Farm Res.* (July 1966).

Table 1: Winter interception measurements obtained in Maine from a mature spruce-fir stand, a moderately well-stocked white and grey birch stand, and an improved pasture.

The rough surfaces of a forest canopy can assist the transfer of water into the atmosphere through turbulence. Forests comprised of different species and ages have varying degrees of surface roughness. The structure of the plant community refers to the entire forest ecosystem. For example a forest community with stratified ages will intercept greater volumes of precipitation in comparison to an even aged plantation due to greater surface roughness at the canopy. Secondary interception occurs in stratified forest communities where water drips from the canopy and is intercepted by lower trees, plants and litter. Lower strata of canopy and ground litter become more important as intensity and duration of the precipitation events increase. Once interception capacity has been reached by the upper canopy, canopy drip is intercepted by underlying vegetation and litter.

Meteorological Factors Affect Interception

There are several meteorological factors that affect interception. Evaporation of canopy-intercepted water is especially affected by available energy; vapour pressure gradient, aerodynamic resistance of the leaves, and air characteristics (humidity) at the canopy's surface. The forest canopy also affects microclimates within the forest. Generally forests have lower air and dew point temperatures, less shortwave radiation, higher relative humidity, and slower wind speed. These characteristics tend to reduce the amount of evaporation of intercepted water as compared to the surface of the canopy.

The precipitation intensity is also an important meteorological factor; water can be delivered too quickly for the plants to hold. The infiltration capacity will be reached much sooner than a low intensity rain event. A larger proportion of low intensity precipitation will be intercepted as the storage capacity is created by drippage and stemflow. The duration of the precipitation event is also important. The duration determines the balance between the storage of water on the vegetative surfaces and increased evaporative losses. Absolute interception storage increases with increasing storm duration; but, because interception decreases exponentially, a larger proportion of short duration precipitation is intercepted. In fact, nearly all the precipitation from a very short storm can be intercepted (i.e. there is no canopy drip or stemflow).

Evaporation tends to increase with increasing wind speed so that during periods of prolonged rainfall, interception loss is greatest in a windy storm; however, the influence of wind is complex and depends on both wind speed and type of precipitation. Increased wind speed promotes interception loss through evaporation. It can inhibit interception until an initial layer of water or snow forms to support further storage (cohesion). Alternatively, wind may increase interception by blowing water into the interior of plants or pushing wet snow against trees and shrubs.

Temperature also has an effect on storage capacity through its modification of water viscosity and surface tension. Interception tends to be greater at lower temperatures. This is especially true approaching and below freezing. The type of precipitation (e.g. rain versus snow) is also a factor. At temperatures around 0ºC, rain can freeze to plants. In 1998 eastern Ontario experience a large ice storm in which ice accumulations measured in total water equivalent of precipitation (freezing rain, ice pellets and a bit of snow) exceeded 85 mm in Ottawa, 73 mm in Kingston, and 108 in Cornwall. Previous major ice storms in the region, notably December 1986 in Ottawa, deposited between 30 and 40 mm of ice - about half the thickness from the 1998 storm event! Snow is more easily blown off or away from plants, but once it sticks, snowflakes (depending on their size, shape and liquid water content) can bridge the gap between leaves, stems and branches; thus the interception of wet snow can be considerable.

The frequency of the precipitation event (i.e. the time between precipitation events) has the greatest significance in terms of the amount of interception. It is thought that this has greater significance than the volume of precipitation and even the duration of the event (Ward and Robinson 1990). Because interception is controlled in many ways by capacity, maximum interception capacity occurs with short duration precipitation events that are spaced sufficiently far apart so that vegetation dries out. Seasonal variation also plays an important role. Conifer trees tend to have consistent interception rates throughout the year because they retain their needles all year. By contrast, deciduous trees exhibit higher interception loss during "leaf on" periods of the year. One example (Lull, 1964) from northern hardwoods and aspen-birch forests experienced summer losses of 15% and 10% respectively, while winter losses were 7% and

4%. Wisler and Brater (1959) suggest that summer losses are 2-3 times that of winter losses for deciduous trees.

Water condensation can occur in the canopy when it comes in contact with fog, especially under high wind speeds. The condensed water in the canopy then falls, adding water to the ground. This added water represents a reverse effective of canopy interception loss. This phenomenon increases with close geographic proximity to oceans and large lakes. It occurs on the edge of the forest stand facing the water body on the leeward side. This can also be called horizontal precipitation, occult precipitation, fog drip, or cloud drip. The type, density, size, and orientation of foliage affect the condensation. Trees with needles such as pine and redwood, are the best condensation collectors (Goodman 1985). Again the surface area (LAI) is the largest contributing factor in this form of interception.

Litter Interception

Litter interception is less significant than canopy interception in terms of volume. The amount of litter interception is largely dependent on the thickness of litter, the water holding capacity, the frequency of wetting, and the evaporation rate. In most cases, litter interception in temperate forests range between a few millimetres and up to 11 mm during a storm. Studies have shown that, in temperate forests, litter can store 25 mm of water prior to infiltration (Cumming, 2000). Forest litter reduces the quantity of precipitation actually reaching the soil but, more importantly, it also affects the velocity of overland flow (also referred to as surface runoff). The reduction of overland flow velocity allows more time for soils to absorb runoff. Forest litter also protects the ground surface from the direct impact of raindrop energy and wind erosion. Forest litter also shades the soil surface, which in turn can reduce soil evaporation. Reducing soil evaporation protects the soil from drying and becoming susceptible to wind erosion.

Runoff and sediment production in areas covered by litter is much less than in bare soil areas (Singer and Blackard, 1978). A loss of vegetative cover raises the temperature and increases the aeration of the soil surface. This increases the breakdown of humus, which is composed of organic material that is generally resistant to decay and remains after animal and plant residues have decayed. As a consequence, more nutrients are released into the soil. Hence a temporary surge in available nutrients often occurs after disturbance. Concurrently, the loss of humus and loss of plant cover lessen the site's ability to retain water. Humus acts as a sponge soaking up water and releasing it slowly into the soil.

Throughfall and Stemflow

The total of throughfall and stemflow is called net precipitation. Throughfall is highly variable; certain drips from points in a stand can cause more throughfall than total rainfall in the open areas. The average throughfall of a stand can be determined by factors such as species, age, density, season, and storm characteristics. For most species, about 2 to 5 percent of gross precipitation flows to the ground along tree stems (Chang, 2003). This is called stemflow. Although it is a small quantity it remains ecologically important as rainwater flows directly into the rooting zone (or root ball) of the tree. One study on oak trees reported 25.4% loss to canopy interception, 20.7% loss to litter interception, and 53.9% of precipitation reaching mineral soils; 3.3% of interception was comprised of stem flow (University of Natal, 2003).

Interception and Water Quality

It has been noted that different land uses affect the local water budget; forest cover intercepts more precipitation than grasslands, for example. This loss will act to increase the solute concentrations of the remaining water reaching the forest floor as throughfall or stemflow, although it will not affect the solute loads (Ward, 1990). Forest cover can also affect the total amount of solutes reaching the ground. A tree's efficient capture of fine water droplets (i.e. horizontal interception of fog) results in greater concentrations of solutes relative to rainfall capture because the proportion of water is lower.

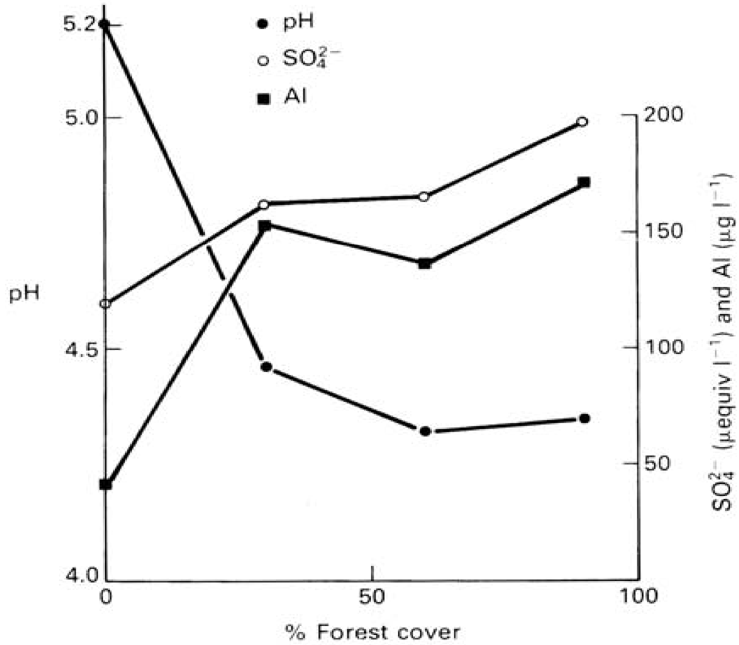
Foliage surface area can also receive deposition of particulate materials which, in turn can be dissolved by precipitation and reach the ground. This is commonly called washoff. Another transfer mechanism, called crown leaching, occurs when leaves absorb gases through stomatal uptake. This material, together with nutrients translocated from their roots and exuded on leaves, may be transferred to rainwater running over them (Ward, 1990). In one controlled study (Cape et al., 1987) the sulphate loads delivered via rainfall only comprised 30% of that reaching the ground via stemflow and throughfall. It was concluded that SO_4^{2-} was leached from the surface of the leaves. This material originated from stomatal uptake of SO_2 gas and deposition of particles containing SO_4^{2-}. Some studies (Clesceri, 1980, Joslin, 1987) examining throughfall suggest that soil acidity is greater under conifer trees than deciduous. This is believed to be due to the fact that conifers are more efficient air pollutant filters.

An experiment conducted in the Hubbard Brook Watershed, where a forest was cleared adjacent to a river and inhibited from growing with herbicides resulted in 50 times the nitrate loading in the river in comparison to uncut control forests in the same watershed (Lickens, 1970). Land use influences the rate of acidification of freshwaters. Forests scavenge both dry deposition and pollutants through occult deposition (fog) very efficiently (especially conifers). This interception, coupled with higher rates of evaporation in trees in comparison to grasslands, results in lower volumes of runoff with higher concentrations of pollutants.

Forests Promote Snow Accumulation

Shelterbelts, also known as hedgerows are linear rows of trees. They have been found to be effective at reducing wind speeds along coasts, deserts, farms, etc. In fact, wind speed can be reduced by 15-60% for a distance of up to 8 times the height of the shelterbelt on the leeward side depending on the density, height, wind direction and width. This has significant ramifications on snow accumulation and delay of snowmelt.

Snow is considered delayed precipitation because of its coverage on the ground in winter and gradual release of water in spring when temperatures rise above freezing. Snow distribution within forests is primarily affected by timber volume and canopy density, while snowmelt in open areas is dependent on temperature, aspect, and elevation. Dense conifer forests intercept the most snow while thin hardwood stands or open areas catch the least amounts. Snow accumulation and the water equivalent are therefore greater in less dense forest areas. Also, as a result of the impact of canopy drips from the saturated snow, snow packs in forested areas are usually denser and have higher free water content than those out in the open.



	Mean pH	*Mean* SO_4 ($\mu equiv\ l^{-1}$)
Ambient precipitation	4.60	54
Moor grass	4.70	124
Oak	4.70	115
12-year-old spruce	4.27	144
25-year-old spruce	4.32	296

Figure 20: Forest cover versus stream chemistry. Mainly sitka spruce, the pH declines and SO42- and Al increase as percent forest cover increases. The table shows mean pH and mean SO42- measured directly beneath various vegetation types (Mason, 1991).

Energy inputs to snow pack are consistently greater in open areas causing the rate of snowmelt to be slower in the forest. The rate of snowmelt on south facing slopes is greater than that on north facing slopes. Field studies have shown that any forest management activity that reduces forest canopies also causes an increase in snow accumulation on the ground in the openings and a subsequent overall increase in water yield. The increase in snow accumulation in the forest openings is due to a reduction in canopy interception and to the redistribution of snow induced by wind effects (e.g. vortex). Cutting small openings into a forest traps more snow, but snow cover in openings disappears faster, reducing water available for soil moisture recharge. Also, the flood potential is high when snow melts rapidly in late spring. The optimal open size for cutting that maximizes both snow accumulation and retention is between 1 and 5 times the height of the trees (Chang, 2003).

Do Forests Promote Precipitation?

There has long been an argument between meteorologists and hydrologists as to the answer to the question - do forests cause rain? There have been many studies (Chang, 2003) that show precipitation occurs in higher amounts in forest areas in comparison to non-forest areas. The majority of the studies have analyzed adjacent plots of land (forested and non-forested) for many years. There are many theories as to why forest may promote precipitation. First, warm air passing over forest may drop its temperature below dew-point by contact cooling, thus promoting condensation and precipitation. Second, forests add effective height to mountains thus promoting orographic[6] precipitation. Third, the rough surface of a forest canopy may slow down an air mass movement causing condensation within the air mass thus promoting precipitation. Fourth and most important, precipitation may be caused by forests due to an increase in water volumes entering the air mass as a result of transpiration in forest areas. One case study in the U.S. in the 1930's showed that planting 200,000 trees in evenly distributed strips stretching from North Dakota to northern Texas, resulted in an increase of local precipitation of 25 percent in some cases. This can be explained by convectional heating of the forest areas causing a rapid rise in the overlying air mass promoting condensation. Also, the forest areas can contribute more dust, acting as condensation nuclei and resulting in more rainfall. Many of these processes are more prevalent in tropical regions. Most scientists agree that forests do not increase or decrease precipitation in temperate regions.

[6] Rain or snow created when air is lifted up the side of a mountain and clouds are formed. Air cools as it rises thus reaching the dew point.

FORESTS AND EVAPORATION

The components of total evaporation from a vegetation covered surface are: bare soil, free water, transpiration, and evaporation from intercepted water. Of these, transpiration and evaporation are the most important in forested scenarios. Evapotranspiration, a very complex process, is the combination of evaporation and transpiration. Both processes occur simultaneously in a forest ecosystem. They are very difficult to differentiate when measuring. Transpiration involves water in the soil moving under the influence of a moisture gradient towards the root hairs of a plant; it is absorbed and then translocated through the plant root and stem system to the leaves or bark, where it is vapourized and exhaled through the stomata or cuticle on leaves or lenticels on bark. Up to 98% of the water taken up by plant roots is lost from an ecosystem to the atmosphere as a result of transpiration. Soil, plant, and atmosphere form a continuous flow path of varying resistance in which water moves at varying rates and undergoes both chemical and physical changes. Each of these stages plays an important role in determining or controlling the total evaporation from the forest.

Albedo and Surface Roughness

As discussed in Part I, evaporation is largely controlled by the atmosphere; primarily by energy and humidity. Albedo is an index of the reflectivity of a surface. The lower the albedo (low reflectance), the higher the absorption of solar energy; an albedo of 1 indicates a perfectly reflective surface, an albedo of 0 a perfect blackbody. Albedo varies between different land cover types and it varies seasonally. Albedo of cleared land is higher than that of forest or woodland.

Surface	Condition	Albedo
Soil	Dark, wet … Light, dry	0.05 … 0.40
Grass	Long (1m) … Short (2cm)	0.16 … 0.26
Crops		0.18 – 0.25
Forest – Deciduous	Leaf off … Leaf on	0.15 … 0.20
Forest – Coniferous		0.05 – 0.15
Water	Small zenith … Large zenith	0.03 … 1.00
Snow	Old … Fresh	0.40 … 0.95

Table 2: Typical values of albedo for selected surface conditions (based on Oke, 1978). (adapted from Ward, 1990)

Surface roughness affects wind, energy transfers and moisture transfers. Rough surfaces dissipate rather than concentrate energy, thereby reducing wind speeds. Vegetation height is very important in increasing evaporation. Trees exhibit an increase in magnitude over grasses in terms of aerodynamic resistance. Trees cause a rougher surface, generating eddy convection, the dominant mechanism in vertical water vapour transport (Calder, 1979).

Surface wetness also affects evaporation. Over vegetated surfaces with a dense plant cover, water losses to the atmosphere are largely accounted for by transpiration. In a dense forest, for example, over 60% of water loss will occur through transpiration. If evaporation of precipitation intercepted by the trees is included, over 80% of water transferred to the atmosphere may be due entirely to the presence of a vegetation cover. Evaporation may compensate for losses by transpiration. In semi-arid areas where there is virtually no surface water, transpiration will account for the entire surface-to-atmosphere water transfer. In dry conditions transpiration losses can exceed that of grasses by a magnitude of two due to larger rooting depth (Calder, 2003).

Evapotranspiration and Soil Water

Compared to water loss in soil evaporation, transpiration has a much larger and deeper evaporating sphere. Vegetative surfaces can transpire larger quantities of water due to their ability to reach deeper water resources through the plant's root system. A shortage of soil moisture limits the rate at which evaporation and transpiration can take place. Under such limiting conditions, actual evapotranspiration is occurring. If, on the other hand, no such limiting condition prevails, then evapotranspiration can take place at its maximum rate within the constraints placed upon it by the: characteristics of the vegetation, the availability of heat energy, the atmospheric humidity and wind speed. Under these non-limiting conditions, potential evapotranspiration is occurring. This concept is used extensively in irrigation studies, as it represents the worst possible situation with regard to water loss from the ground surface.

Transpiration is reduced when leaves have intercepted precipitation on their surface. The water on the surface of the leaf essentially seals it. The water must first evaporate off the surface of the leaf before transpiration can take place. In the case of wetted vegetation, the evaporation of intercepted water takes place at a much higher rate than the transpiration of water through stomatal diffusion. Furthermore, Pearce (1980) reported that evaporation of intercepted water is more important to the water budget where surface wetting occurs at night rather that during the day.

Soil evaporation is the least important component of total evaporation, where vegetation cover is approaching continuous. Even when groundwater is close to the ground surface (<120cm) the water losses from transpiration exceed that of soil evaporation by approximately 100 times (Veihmeyer, 1938). In forested areas where cover is less continuous, albedo and wind turbulence play a larger role. In a comparison between forest, meadow grass, and cultivated crops, soil evaporation contributed 10%, 25%, and 45% respectively to the total evaporation (Ritchie, 1972 and Baumgartner, 1967). This study emphasizes the ability for forest cover to protect soil water.

Evapotranspiration and Cover Type

Since transpiration reduces soil moisture content, the storage capacity of the soil for water is increased. Therefore, if vegetative cover is reduced, the transpiration is reduced and the soil has a lower capacity to absorb water. This results in greater runoff. The combination of greater free nutrients (due to humus decay) and increased runoff results in increased nutrient loss from disturbed systems. A case study on the Hubbard Brook Experimental Forest illustrated that when land is deforested, nutrient counts in adjacent stream water increased dramatically. In the second year, nitrate levels had increased by 56 times the normal levels (greater than the recommended concentration acceptable for drinking water). Post clear-cutting, the growth of vegetation began to capture the nutrients and then nutrient loss was reduced.

Evapotranspiration in forested watersheds is greater than in non-forested watersheds. Consequently, deforestation causes a reduction in actual evaporation and the conserved water will contribute to increases in water yield. In forested watersheds, the loss of water is from the forest's large transpiration surface, deep root system, canopy interception loss, wind, and available energy. Soil evaporation occurs only at the soil surface and is active only in the surface layer.

Cover Type	Evaporation (%)	Interception (%)	Transpiration (%)
Forest stands	10	30	60
Meadow	25	25	50
Cultivated	45	15	40
Bare soil	100		

Table 3: Approximate Components of Vapourization for Various Land Uses in Germany (Chang, 2003).

The surface area (LAI) of a tree (canopy) is often several times greater than the surface of the ground. A typical leaf area index for a tree is five to seven; this number could be as high as 40 for a mature, mixed stand of spruce and fir trees (Kaufman, 1982). A large volume of available water in the soil, coupled with a greater surface area, makes transpiration rate and duration from trees higher than vaporization from bare soils or short vegetation.

Effect of Forest Species on Evapotranspiration

Each forest species has its own unique characteristics with respect to height, canopy density, root systems, colour, stomatal response to environmental stress, leaf orientation, the length of growing season, and changes in foliage with seasons.

Species	ET (mm/d)	Study duration	Location	Method	Reference
Conifers					
Douglas fir	2.1	3 growing seasons	Seattle, WA	Lysimeter	Fritschen et al., 1977
Slash pine	3.0	4 years	Gainesville, FL	Lysimeter	Riekerk, 1985
Ponderosa pine	3.3	2 growing seasons	Alpine, AZ	Energy budget	Thompson, 1974
Ponderosa pine	2.0	14 years	Globe, AZ	Water balance	Rich and Gottfried, 1976
White pine	3.1	2 years	Coweeta, NC	Simulation	
Shortleaf pine	2.2	5 years	N. Mississippi	Water balance	Ursic, 1991
Pinyon-juniper	1.2	10 years	Flagstaff, AZ	Water balance	Baker, 1984
Spruce-fir, etc.	1.2	Long-term	Frazier, CO	Water balance	Leaf, 1975
Hardwoods					
Alder, maple	1.6	7 years	Toledo, OR	Water balance	Harris, 1977
Aspen	1.5	4 years	Bountiful, UT	Soil moisture	Johnston, 1970
Live oak	1.4	10 years	Lincoln, CA	Water balance	Lewis, 1968
Oak-hickory	2.6	2 years	Coweeta, NC	Simulation	Swift et al., 1975
Oaks, maple	2.4	9 years	Parsons, WV	Water balance	Reinhart et al., 1963
Saltcedar	7.2	1 growing season	W. Arizona	Energy budget	Gay, 1986
Yellow poplar	1.7	2 years	E. Tennessee	Water balance	Luxmoore et al., 1978

Table 4: Average Daily Evapotranspiration (ET) Rates for Various Forest Species in the United States (Chang, 2003).

These characteristics affect the amount of available energy in the forest and the ability of a plant to transpire water. Direct comparisons between species are difficult due to the many variables found at each site; however, it is interesting to note the difference between conifer and deciduous tree species. Species composition in a forest thus has a great impact on stream flow quantity.

Canopy resistance changes with the seasons for deciduous species. Hardwood species loose chlorophyll in the fall at different rates and at different times. This results in further differences in transpiration between species.

On the regional scale, there has been controversy as to whether vegetation cover can influence rainfall through its effects on evaporation losses. Early notions of vegetation's influence over the amount of rainfall were largely dismissed by later work which emphasized the large-scale nature of water vapour-precipitation relations. Great distances often separate the evaporation of water and the subsequent precipitation (Penman, 1963). Studies in the tropical basin of the Amazon Forest indicate that about half of the total precipitation originates as transpiration (Salati and Vose, 1984) (Shuttleworth, 1988). Continued large-scale deforestation will lead towards reduced evaporation, increased runoff, and reduced precipitation in the region. It has also been suggested that vegetation changes could be the cause of decreased amounts of rainfall (Charney, 1975). Overgrazing can also reduce the vegetative cover, exposing more sandy soil, increasing the albedo of the ground surface (i.e. higher reflection). This, in turn, lowers the ground surface temperatures, reducing the likelihood of convective heating.

FORESTS AND STREAMFLOW

Streamflow is defined as a body of water moving over the ground surface in a network of channels. It is also often called discharge or runoff. Streamflow is a combination of precipitation, overland flow, interflow, and baseflow.

Runoff and Infiltration

Runoff is precipitation running over land or through the soil profile to a nearby stream or body of water. Runoff generally takes place when precipitation exceeds the soil's infiltration rate. This does not necessarily mean the soil surface has to be saturated. Any factor that reduces the amount of rainfall contacting the ground or increases the amount of water retention in the soil, affects the amount of runoff. These factors are collectively known as watershed storage, retention, or abstraction. They can include depression storage, interception, snow pack, and bound soil moisture.

Precipitation is first intercepted by the canopy and litter before reaching the ground. The initial rainfall that does contact the ground is called surface detention; this initially wets the ground surface facilitating infiltration of further rainfall. The rainfall that reaches the ground is called effective rainfall. Effective rainfall can account for 70-80% of the gross rainfall in a forested area (Chang, 2003). Rainfall intensity refers to the amount of rain that falls in a unit of time and is measured by a recording rain gauge.

Infiltration is the movement of water into the soil. The driving forces promoting infiltration are capillary attraction and gravity. The maximum rate at which a given soil can absorb water is called infiltration capacity. During a precipitation event the infiltration rate is initially high. This is due to large voids caused by animals and roots filling with water. As the duration of the storm progresses the infiltration rate approaches a constant controlled primarily by the rate of water draining under the force of gravity. This process of water migration through the soil profile under gravity is called percolation.

As one might expect, infiltration and percolation are affected by soil surface conditions as well as the composition of the soil. Ponding, overland flow velocity, and infiltration are significantly affected by cover type, ground surface roughness, and slope; to a lesser degree, aspect, and chemicals also affect these processes. The soil water holding capacity and percolation rates under the soil surface are affected by soil texture, structure, depth, organic matter content, compaction, water content, and root systems.

Soil is comprised of solid particles, water, and gas. The ratio of the volume occupied by gas and water, and the volume occupied by solid particles is called the porosity. Coarse soils have smaller porosity than fine soils. As a result the infiltration rate, rate of water movement, and water holding capacity is generally greater for finer soils.

Runoff occurs when effective rainfall exceeds the accumulated infiltration. Initially, the soil water deficit is high and a lot of rain is able to enter the soil. Gravity and capillary forces pull water down into the ground filling both big and small pores. As pores fill up, infiltration slows down, eventually, causing percolation and infiltration to be equal. The ground's ability to retain more water is reached and therefore runoff is formed.

Even infiltrated water can become runoff. The soil water can flow laterally and down, joining subsurface flow to later wind up in a nearby stream. Forested areas usually have deep, loose soils, and extensive root systems; these areas have high infiltration capacities. As a result, streamflow responses to storm events are usually slow and small in volume. Effective precipitation being lower in forested areas due to interception is a contributing factor. The majority of water movement occurs under the soil surface (interflow). Surface runoff is the culprit causing quick streamflow in a watershed; forested watersheds usually have little surface runoff. Beasley (1976) reported that in forested watersheds, interflow could account for more that 90% of effective rainfall.

Watershed Discharge and Yield

Plant cover is a very important factor in the hydrologic cycle. Canopy and root systems affect the majority of processes that impact watershed discharges, including: precipitation, interception, infiltration, percolation, surface detention, surface roughness, transpiration, snow accumulation, and snowmelt.

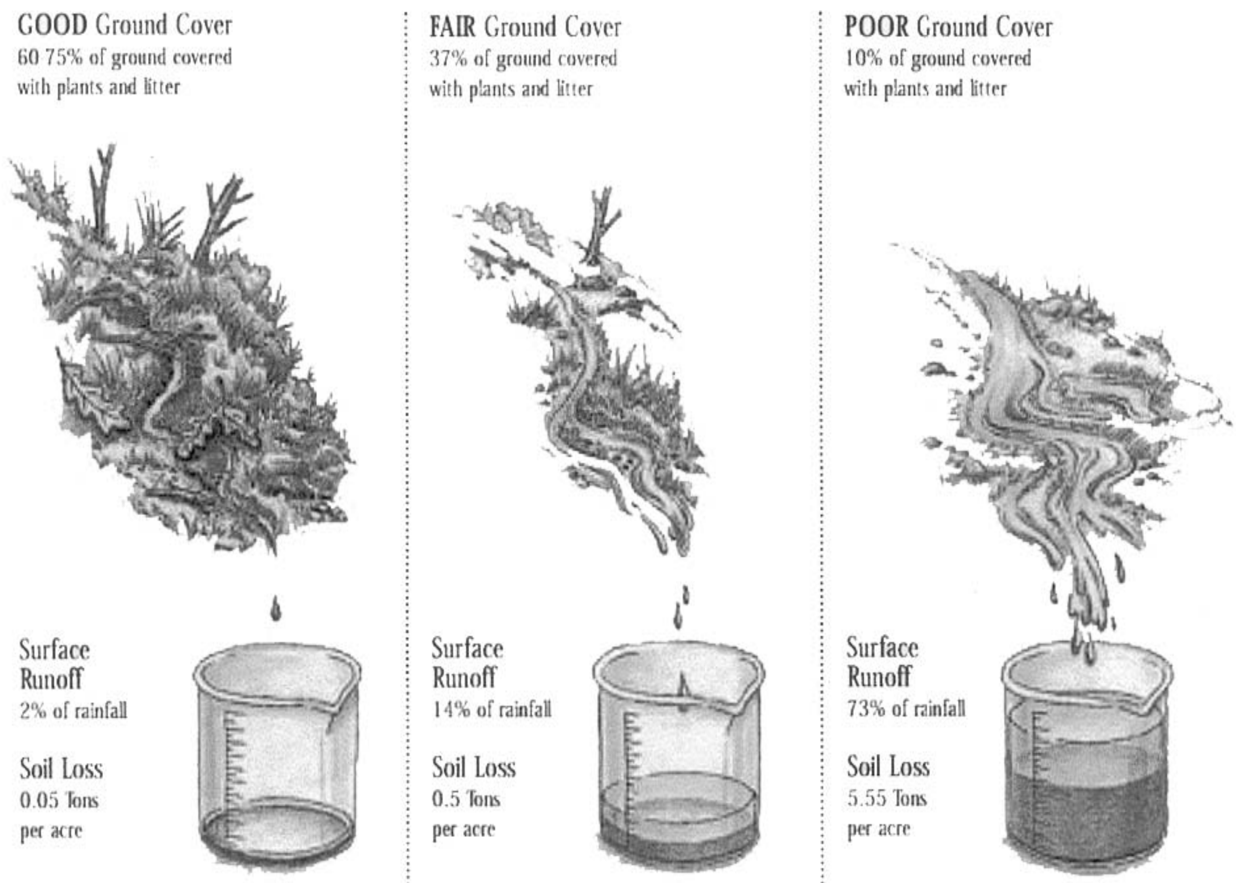
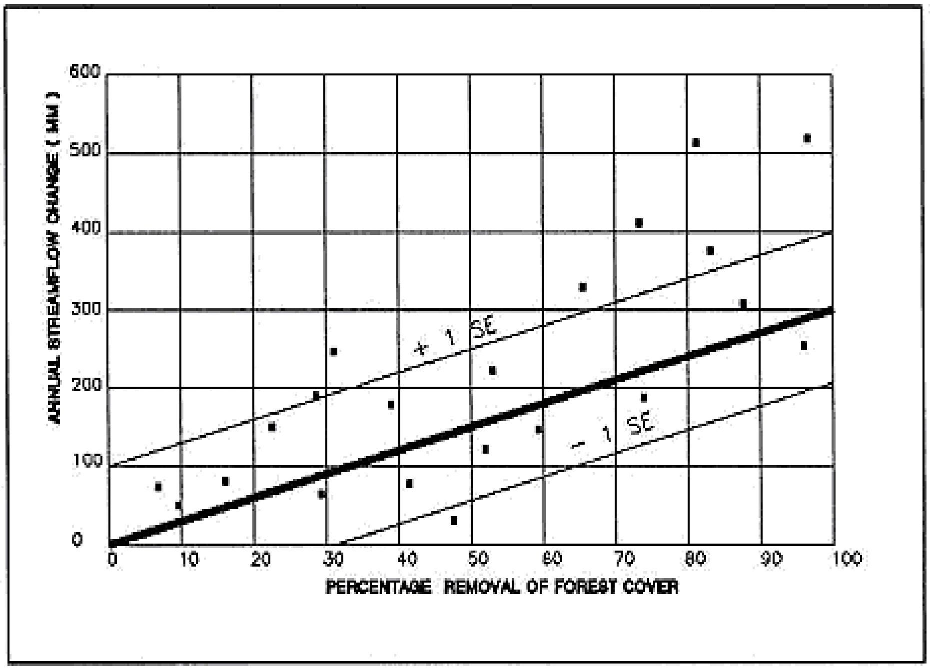


Figure 21: Experimental results of the effects of watershed condition on rainstorm runoff and erosion (data from Great Basin Experimental Area, Utah) (USDA, 2000)

The removal of forests usually results in increased water yield. Increases in runoff have been found to be proportional to the area of forest removal (Hibbert, 1967). Where 20 - 100% of the forest is removed, increases of 100-300 mm/yr have been recorded.



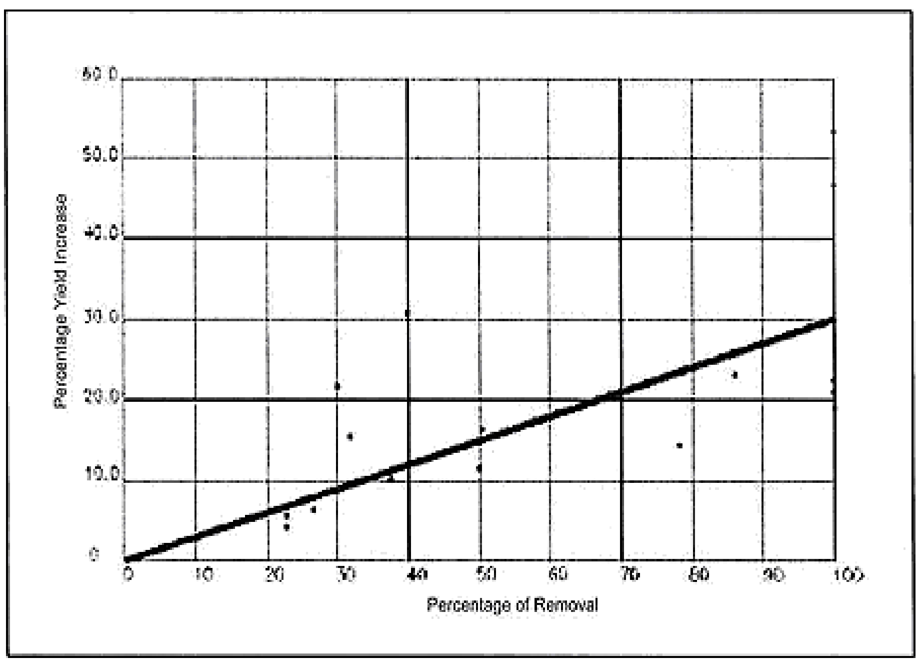


Figure 22: Relationships between yield and percent forest cover (Hibbert, 1967)
Yields are greatest from a watershed when cutting is focused on conifer species, followed by hardwoods.

Watersheds dominated by grasses exhibit the least amount of change in water yield after cutting. The USDA (2000) reported that areas that experience great yield changes have greater than 15 inches of precipitation per year. Not surprisingly, areas with this much rainfall are generally dominated by mixed conifer species (spruce, fir, lodgepole pine) and eastern hardwoods. It is important to note that forest management activities that incorporate multiple use values have a relatively low impact on water yield. Harr (1983) and Kattelmann (1983) report that even in wet environments, increases could be as low as 1% under sustainable forest management. A forested watershed will produce a hydrograph with lower peakflow, smaller volume of runoff, and broader time base than a watershed that has been cleared, cultivated, or pastured (Chang, 2003).

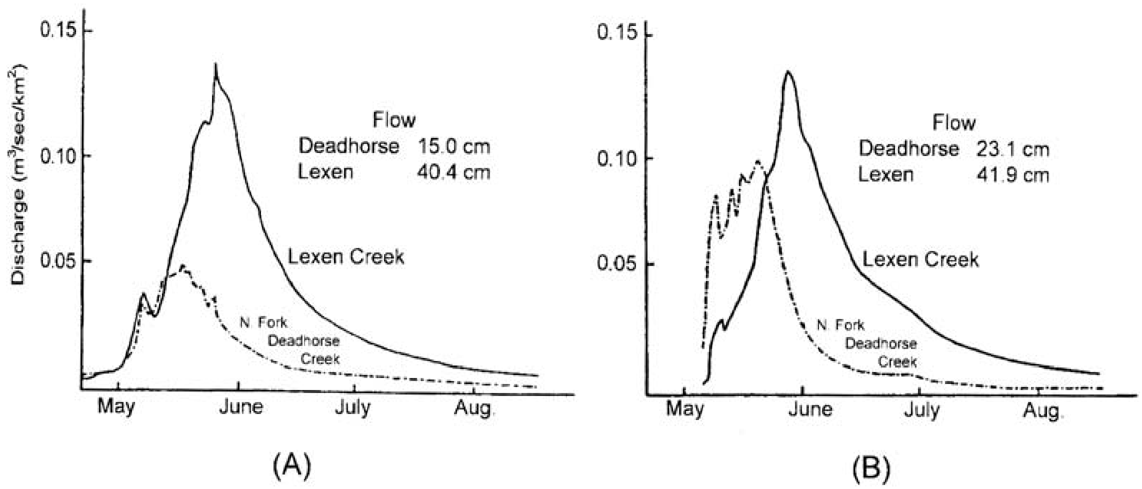


Figure 23: Experimental results of the effects of watershed discharge before and after forest cutting. (B) forest cutting. The subalpine forest in the North Fork, Deadhorse Creek watershed was reduced by 36% through patch cutting (1.2 ha patches). Stream flow increased 55% after treatment. (Troendle, 1983).

Both the percent forest cover and size of the watershed play very important roles in determining stream flow. The water yield is greater with lower percent forest cover and larger watershed area. In a pine-dominated watershed in east Texas, a 10% reduction in forest cover resulted in a 20mm increase in stream flow (Chang and Waters, 1984). Cumming (2000) reported average increases of 40mm, 10-25mm, and 10-25mm in annual watershed yield resulting from a 10% reduction in forest cover for basins dominated by pine, deciduous, and scrub respectively. Differences in streamflow between forested and non-forested watersheds could be as much as 200mm.

Soils without vegetation mainly cause surface runoff, with a minimal rate of runoff delay and infiltration. In a comparative study between two mountainous watersheds (87% and 12% forest cover) in France, it was estimated that forest cover cut the peak flow of a storm event by at least 80 percent and runoff volumes by at least 40 percent (Meunier, 2003). In the same study it was shown that peak flow rates of the forested watershed and the degraded watershed vary by a factor of 10. The forest cover plays an effective role in intercepting the rain, acting as a temporary storage reservoir to soak up runoff and reduce the velocity of the flow.

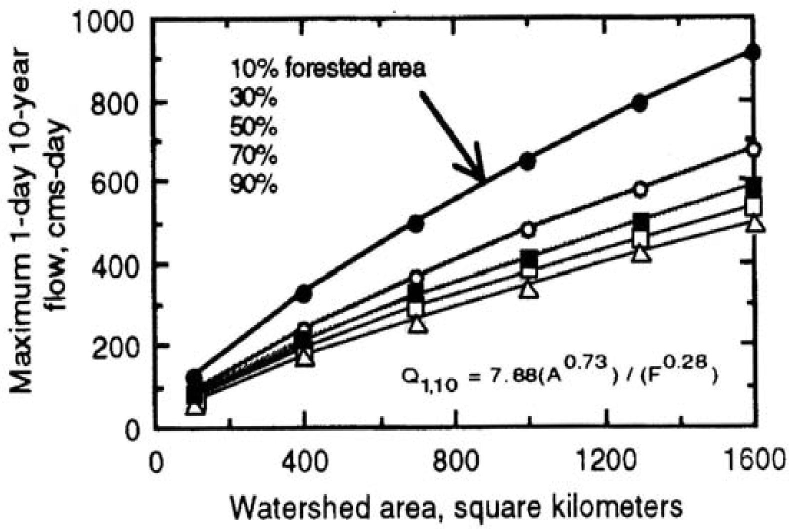


Figure 24: Streamflow as a function of watershed area and percent forest cover. (Chang and Waters, 1984)

Vegetation also influences streamflow through the shade forests provide. The shade reduces temperature and airflow at the soil surface, slowing the release of nutrients from the decomposition of humus. Transpiration increases, therefore reducing the runoff due to increased storage capacity in the soil. Forest cover can reduce stream output by 25% through transpiration alone.

FORESTS AND STREAM SEDIMENT

Sediment refers to soil particles that enter streams, lakes, and other bodies of water from eroding land, including plowed fields, construction and logging sites, urban areas, and eroding stream banks (U.S. E.P.A. 1995). The sediment may come from rocks, soil, or biological materials in the watershed and are carried to stream channels in runoff, debris flow, channel and bank erosion, or wind erosion. Not all soil erosion is deposited in streams; approximately 2-10% of the erosion occurring in a watershed results in stream sediment (Stednick, 2000). This sediment can damage the physical, biological and chemical properties of a stream. Sedimentation of streams can have a pronounced effect on water quality and stream life; it can clog and damage fish gills, suffocate fish eggs and aquatic insect larvae, and cause fish to modify their feeding and reproductive behaviours. Eroding sediments may transport other substances such as plant and animal wastes, nutrients, pesticides, petroleum products, metals, and other compounds that can cause water quality problems (Clark 1985).

The rise and fall of sediment concentrations serves as a good indicator for the success of particular watershed management techniques. Vegetation is considered an effective and relatively maintenance free method of controlling both soil erosion and stream sediments. Watersheds with undisturbed forest cover have erosion rates far lower than those that have been harvested; however, using best management practices (BMP) when conducting forest management results in considerable improvements.

In a recent study (Mostaghimi, S. et. Al., 1999) three small watersheds located in Westmoreland County, Virginia were monitored to evaluate the impact of forest clearcutting on surface water quality and to evaluate the effectiveness of forestry best management practices (BMPs) for minimizing hydrologic and water quality impacts associated with timber harvesting. One watershed was clearcut without implementation of BMPs, one watershed was clearcut with the implementation of BMPs and the third watershed was left undisturbed as a control. The 28 months of pre-harvest monitoring data and of post-harvest monitoring data were compared.

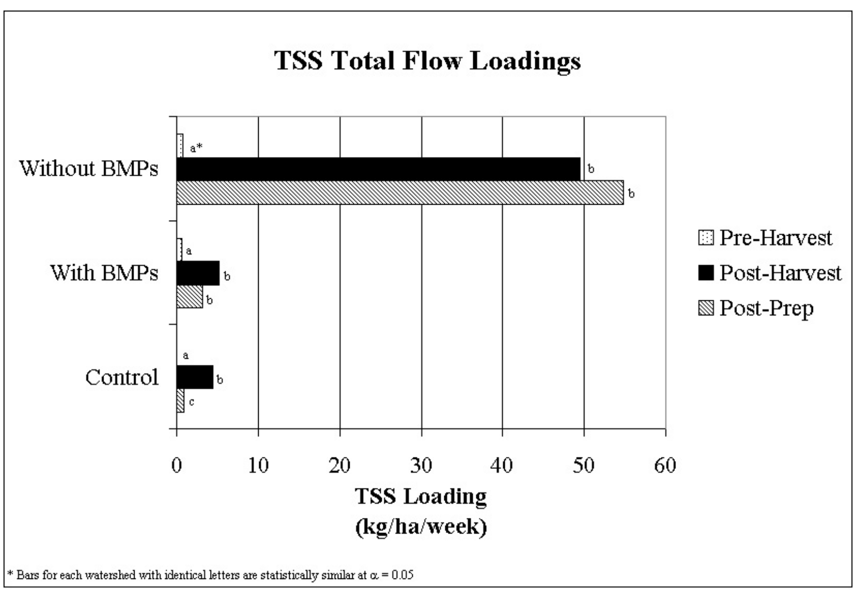


Figure 25: Total Suspended Solids (Mostaghimi, S., 1999)

Forest clearcutting without BMP implementation reduced storm runoff volume and peak flow rates. For the watershed with BMP implementation, storm flow decreased significantly following harvest, while peak flow increased. Disruptions in subsurface flow pathways during harvest or rapid growth of understory vegetation following harvest could have caused these hydrologic changes.

Harvest and site preparation activities significantly increased the loss of sediment and nutrients during storm events. Storm event concentrations and loadings of sediment, nitrogen, and phosphorus increased significantly following forest clearcutting of the no-BMP watershed. Most of the nitrogen and phosphorus was associated with particulate material. Both the BMP watershed and the control watershed showed few changes in pollutant storm concentrations or loadings throughout the study. Silvicultural activities also significantly increased sediment loss from the no-BMP watershed on a total flow basis (storm flow and base flow).

Results of this study indicate forest clearcutting and site preparation in the Virginia coastal plain cause significant increases in sediment and nutrient concentrations and loadings, particularly during storm events. Comparing forest clearcutting to site preparation activities, the herbicide treatments and burning during site preparation had a greater impact on water quality than the timber harvest. Estimated annual sediment yields following harvest of the no-BMP watershed were higher than those measured in areas of row crop production within the Nomini Creek watershed. At the same time, the loss of sediment from the watershed where a system of BMP's was implemented was similar to the loss from the control watershed. The best management practices appear to have been effective at maintaining pre-harvest storm total suspended solids (TSS) concentrations and loadings, even during a period of intense precipitation.

A Mechanical Barrier to Erosion

Vegetation resists against soil detachment resulting from both rainfall and runoff. The canopy of a forest reduces the terminal velocity of raindrops through interception. Canopy interception depends on the height and density of the canopy. Canopies at ground level are generally more effective than high ones because they act like a blanket shielding the ground from drops that fall off of a higher canopy. Higher canopies also allow precipitation to regain velocity through canopy drip. Ground canopies also add roughness (through increased stem density) to the ground surface, slowing runoff velocity.

The root systems and organic matter content in a forest increase the cohesive and frictional mechanisms of the soils shear strength, thereby contributing to soil stability. Deep root systems are excellent at stabilizing steep slopes. Roots are capable of anchoring the soil's mantle to the substrate. Fine, shallow roots are good for protecting the ground from raindrop and wind erosion. Fine roots and decomposed organic matter add to the formation of stable soil aggregates, protecting the soil from erosion in the future. The failure of soil on slopes is related to the shear strength of the soil. This shear strength is directly related to the biomass of roots in the soil. Smaller roots (diameter) tend to have greater tensile strengths than thicker roots. Roots that grow uphill are stronger than those growing downhill. Roots also tend to be strongest in the fall when they are growing the most. Root strength declines with age. Gray and Sotir (1996) showed that deciduous trees and shrubs have greater root tensile strength than conifers.

Vegetative hydrological functions are also very beneficial. Interception loss, reduced net precipitation reaching the soil, transpiration depleting soil moisture, and litter and organic matter slowing flow velocity, all lead to an increase in infiltration and a decrease in the sediment-transport capacity in runoff. Forests have been found to reduce erosion more than other types of vegetation because of their great size and density. In 1977, Dunne observed that stream sediment was the lowest in watersheds with greater forested area. The greatest sedimentation occurs in grazed watersheds where vegetative cover and soil structures were destroyed, compaction was great, and infiltration rates were lower. Forested watersheds disperse flows and reduce flow energy resulting in less detachment and transport of soils.

Studies indicate that forested riparian buffers can effectively trap sediment. In North Carolina, scientists estimated that 84 to 90 percent of the sediment from cultivated agricultural fields was trapped in an adjoining deciduous hardwood riparian area (Cooper et al., 1987). Sand was deposited along the edge of the riparian forest, while silt and clay were deposited further in the forest. Buffers may be most effective at removing large particles such as sand, but may be less effective at removing small clay particles. Along the Little River in Georgia, scientists found that a riparian forest had accumulated 311,600 to 471,900 pounds per acre of sediment annually over the last 100 years (Lowrance et al., 1986).

Many factors influence the ability of the buffer to remove sediments from land runoff, including the sediment size and loads, slope, type and density of riparian vegetation, presence or absence of a surface litter layer, soil structure, subsurface drainage patterns, and frequency and force of storm events (Osborne and Kovacic 1993). Riparian buffers must be properly constructed and regularly monitored in order to maintain their effectiveness. Probably the most important consideration is the maintenance of shallow sheet flow into, and across, the buffer. Where concentrated flow paths begin to form or deep sediments begin to accumulate, the buffer can no longer maintain its filtering ability.

Conservation Plants & Protection Forests

Although basically all seed plants are beneficial for minimising soil erosion, conservation plants and protection forests are defined as vegetation that are useful for the control of soil erosion and land reclamation. Soil conservation ability varies among different species. The selection of an appropriate conservation plant is based on the intended purpose of the plant, the cause of the erosion problem, and the site conditions. The site conditions are determined based on a number of factors including soil, topography, and microclimate. A conservation plant must fit all three categories in order to be efficient.

In general, plants that are growing on similar sites are good choices for remediation planting. Native species are always better than exotics. A combination of many species provides compensation for single species deficiencies.

Physiological	Morphological	Managerial
Growth rate, vigorousness	Canopy density	Availability of plant
Tolerance to drought, soil pH, flooding, grazing, and extreme temperatures	Shape of plants, individual, clump, creeping, vine, etc.	Environmental nuisance
		Harmful effects to man and animals
	Height of clean stems (height below the canopy)	
Regrowth ability		Plant sources
Method of generation	Root systems	
Adaptability to the sites		
Productivity of forage, litter		
Species competition		
N-fixation ability		
Palatability to wildlife		
Evergreen or deciduous		

Table 5: Plant characteristics to look for when picking species for erosion control. (Chang, 2003)

FOREST PRACTICES AND WATER QUANTITY

Forest transpiration is much greater than soil evaporation because of the effects of the canopy, litter, deep roots and higher energy level. In forests, compensation for increased evapotranspiration can be found in a reduction in runoff. Removing trees, even if smaller plants have been planted in their place, leads to greater streamflow. Much research in the 1970's was dedicated to how forest management techniques could be used to augment water yields to alleviate water shortages. Forest practices are generally less severe today because society has accepted that water yield augmentation is but one of the multiple uses and benefits forests play in our environment.

Forest clearing leads to an increase in water yield. The water yield generally decreases after a cutting event due to re-growth of vegetation in the cleared area. Generally, the clearing effects are shorter in humid regions and in plant species with deeper root systems. Water yield is also affected by the rainfall characteristics of the site. Areas with greater amounts of rainfall will produce larger storm events, resulting in higher peak flows. The factors that increase water yield include: the amount and timing of precipitation, the intensity of forest cutting, forest species, and soil topography.

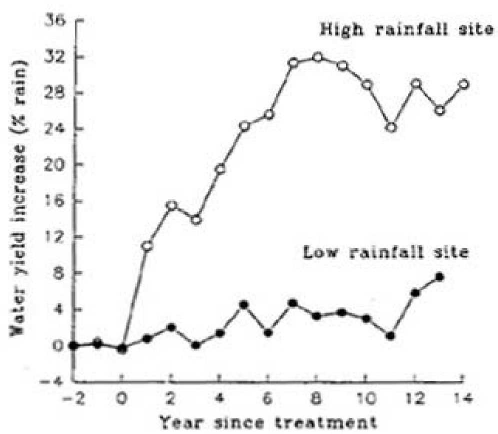


Figure 26: Comparison of water yield responses to clearing for agriculture for different rainfall zones. (University of Western Australia, 2003)

Intensity and distribution of forest management affect water yield in a watershed setting. Clear cutting the entire watershed yields the maximum increase, while thinning yields the minimum. Water yields can be increased between 10-65% through forest clearing; however, complete forest clearing can impose adverse effects such as nutrient losses, soil erosion, lower water quality, and less aesthetic environments. Forest management should employ less intensive cutting or small clearings. Folliott and Thorud (1977) suggest that small openings in the watershed can benefit timber and wildlife resources. Increases in the water yield by partial cutting are lower than clear-cutting, depending on intensity and distribution of the cutting.

Douglass (1983) developed an equation which models water yield after harvesting hardwoods. As an example, if a watershed of eastern hardwoods was clearcut, it would take 16 years for the water yield to return to pre-treatment levels. However, if the same watershed was cut to 50% of its basal area, pre-treatment water yields would be achieved 6 years after treatment. The harvest method has a large bearing on the increase in water yield. A 67% selection cut in a watershed dominated by redwood and Douglas fir caused an increase in water yield by 15% (Keppeler and Ziemer, 1990). In a watershed dominated by lodgepole pine, a 25% patch cut resulted in an increase in water yield of 52% (Burton, 1997). Troendle and King (1987) report that single tree selection cutting or thinning does not produce large increases in water yield. A study in Arizona showed that thinning a stand's basal area up to 6.9m2/ha did not result in a great increase in water yield (Baker, 1986).

Region	Forest Type	Water Increase		Reference
		mm	%	
The East				
Coweeta, NC	Mixed hardwoods	427	65	Hewlett and Hibbert, 1961
Hot Springs, MS	Shortleaf pine	370	38	Ursic (1991)
		116	13	
Hubbard Brooks, NH	Mixed hardwoods	343	40	Hornbeck et al., 1970
Leading Ridge, PA	Mixed hardwoods	137	23	Lynch and Corbett, 1990
Fernow, W. VA	Mixed hardwoods	130	19	Reinhart and Trimble, 1962
Bear Creek, AL	Pine-hardwoods	297	60	Betson, 1979
The Northwest				
H. J. Andrews, OR	Douglas fir	462	39	Rothacher, 1970
H. J. Andrews, OR	Douglas fir	420	27	Harr et al., 1982
Coyote Creek, OR	Douglas fir and pine	360	39	Harr et al., 1979
The North				
Marcell Experimental Forest, MN	Aspen-birch	81	39	Hornbeck et al., 1993
The Rocky Mountains				
Fool Creek, CO	Alpine and subalpine	94	36	Troendle and King, 1985
Wagon Wheel Gap, CO	Bristlecone pine	15	8	Bates and Henry, 1928
The Southwest				
Beaver Creek, AZ	Ponderosa pine	99	63	Baker, 1986

Table 6: Selected results of the effect of clear cutting on water yield one year after treatment. (Chang, 2003)

Plant transpiration rates differ among species because of different characteristics in canopy, height, and root systems. Generally, conifers have greater total leaf surface area and retain foliage year round. In general, transpiration rates are greatest for conifers, followed by hardwoods, chaparrals, and grasses. Converting species composition within a watershed to species with lower transpiration rates will increase water yield.

Management of riparian vegetation can also affect stream flow. In 1971, Ingebo suggested that water yields could be increased through mechanical eradication or transpiration suppression. For water yields to be affected however, (a) the water supply must exceed evapotranspiration after treatment, (b) the water table is within reach of the riparian vegetation, and (c) the soils are deep enough to allow the water table to lower after treatment. Treatments of this nature are discouraged because they can lead to water quality and erosion problems.

Location	Precipitation (mm/year)	Original Vegetation	Conversion Treatments	Effects on Water Yield (mm or %)		Reference
Sane Creek, WY	572	Sagebrush	Control by 2,4-D	+11 mm,	11 years	Sturges, 1994
Whitespar, AZ	660	Chaparral	Herbicides control	+69 mm,	7 years	Davis, 1993
Mingus, AZ	480	Chaparral	To grass by fire	+10 mm,	5 years	Hibbert et al., 1982
Three Bar, AZ	673	Chaparral	To grass by fire	+148 mm,	18 years	Hibbert et al., 1982
Mendocino, CA	920	Oaks	2,4-D to grass	+39%	10 years	Pitt et al., 1978
Placer County, CA	620	Oaks, forb	2,4-D to clovers	+113 mm	3 years	Lewis, 1968
Beaver Creek, AZ	460	Pinyon, etc.	2,4-D to forbs	+157%	8 years	Baker, 1984
Coweeta, NC	1854	Hardwoods	Cut to fescue	+78 mm	5 years	Hibbert, 1969
Coweeta, NC	1930	Hardwoods	Cut to white pine	−64 mm	4 years	Swank and Miner, 1968
Boco Mt, CO	259	Sagebrush	Plow to wheatgrass	−9 mm	6 years	Lusby, 1979

Table 7: Effects of species alteration on water yield. (Chang, 2003)

Soil and topography are considerations in predicting water yield. Deep soils comprised of fine textured materials have greater water holding capacity than shallow coarse soils. Basins comprised of these deep fine soils will control runoff better, resulting in lower water yield. Slope and aspect contribute to the impact of solar radiation and wind speed; this ultimately affects soil and air temperature regimes and evapotranspiration rates, which, in turn, determine vegetation type and growth. Forest transpiration is generally greater in northern slopes because of denser vegetative cover and deeper soils (Bethlahmy, 1973). Douglass (1983) and Cline et al. (1977), observed that clearcutting south facing slopes resulted in one third the increase in water yield in comparison to north facing slopes in North Carolina and Idaho, respectively.

Forest management and the seasonal variation in streamflow are important. The main reason water yields increase as a result of forest clearing is the reduction of interception and transpiration. In areas like eastern Ontario, where precipitation is dominated by rainfall with no significant distribution pattern throughout the year, most stream flow increases occur in the summer and fall under natural conditions. Cutting in the winter and spring, where soils are saturated and evapotranspiration is low, results in little change in streamflow.

Are forests streamflow moderators? It has been noted above that forest harvesting increases water yield. These increases are a result of increases in low flow or increases in peak flow, or both. Peak flows are generally inversely related to percent forest cover in a watershed (Reich, 1972). Low peak flows occur in forested watersheds and high peak flows result from forest cutting. Some of the causes of increased peak flow following forest harvesting include more saturated soils, soil compaction, and road construction. As discussed earlier, the intensity of the cutting has a great impact on the peak flow. Harvesting closer to the water course can result in quicker peak flows. Harr (1979) reported that as long as the forest floor is kept intact, the effect of clear cutting on peak flows could be significantly reduced. After cutting, most of the streamflow increase is in the form of baseflow. Hornbeck (1970) found that in the Hubbard Brook Experimental Forest, only 35.4% of the increased streamflow was a result of quick overland flow.

Forests are the most effective types of vegetation in reducing streamflow due to the great amount of transpiration and increased soil-water holding capacity; however, they cannot be relied on for flood control. Once soils are saturated (whether forested or barren), overland flow will occur unimpeded. Forests therefore are excellent streamflow moderators for short, low intensity storm events, but not as good under long intense storms. The majority of increased water yield as a result of timber harvesting can be attributed to increased low flow levels. In the H.J. Andrews Experimental Forest in Oregon the number of low flow days increased from 8 to 143 as a result of clearcutting a watershed; also, in a watershed that underwent a shelterwood cut, the number of low flow days increased from 2 to 135 (Harr, 1982). In West Virginia, it was shown that after forest harvesting, the magnitude and frequency of low and high flows were increased in both wet and dry years (Reinhart, 1963). In North Carolina, Swank and Vose (1994) reported a reduction in the frequency of high and low flows when two watersheds were converted from eastern hardwoods to white pine plantations.

In eastern Ontario the variance in topography is relatively low, subsurface conditions are relatively uniform and the movement of groundwater is slow. Under this situation forests tend to lower the groundwater table. Studies have shown that fluctuations in groundwater tables are caused by changes in transpiration rates, forest type, harvesting intensities, and land use conditions. Harvesting a forest will result in lower transpiration and reduced interception, resulting in a higher water table. In one study in Australia, a forested watershed was completely cleared for agriculture. The water table rose 2.7 metres/year over 4 years. This was calculated to be equal to a 6-12% increase in precipitation for the area (Peck and Williamson, 1987).

FOREST PRACTICES AND WATER QUALITY

Forests provide the best mechanisms in nature to protect watersheds against soil erosion and nutrient loss through their canopies, litter, and root systems. These characteristics and the water cooling effects of riparian vegetation produce higher quality water than other landuses. However, because many forests are managed for their resources, the balanced ecosystem can be disrupted and water quality can be jeopardized.

Land Cover	Concentration (mg/l)		Yield (kg/ha/year)	
	Total N	Total P	Total N	Total P
≥90% forest	0.598	0.018	3.47	0.091
≥75% forest	0.643	0.024	3.54	0.129
≥75% rangeland	1.297	0.097	1.04	0.065
≥40% urban	1.818	0.092	7.30	0.347
≥75% agriculture	2.702	0.140	5.55	0.255
≥90% agriculture	5.354	0.161	9.54	0.266

Source: Omernik, J.M., 1976, Nonpoint Source–Stream Nutrient Level Relationships: A Nationwide Study, EPA-600/3–77–105, EPA Environ. Res. Lab., Corvallis, OR.

Table 8: Mean Concentrations and Yields of Nitrogen and Phosphorous under Various Cover Conditions in the U.S. (Chang, 2003)

Water quality can be examined by analyzing the levels of physical, chemical, and biological properties. Forested watersheds tend to have better water quality than other landuses. Higher water quality in forested watersheds can be attributed to: greater nutrient uptake by plants, fewer runoff and sediment losses, lower rates of organic matter decomposition, cooler temperatures, and less management activities (Chang, 2003).

	Forested Streams	Agricultural Land	Reference
Total Nitrogen (N)	0.850 mg/L	4.170 mg/L	(Chang, 2003)
Total Phosphorous (P)	0.014 mg/L	0.135 mg/L	(Omernik, 1976)
Conductivity	3-15 mS/m	276-3855 mS/m	(Binkley, 1993) (Lewis, 1998)

Table 9: Average Total Nitrogen, Total Phosphorous, and Conductivity for Forested vs. Agricultural Areas. (Chang, 2003)

Forest practices can affect stream sediment loads, stream temperature, concentrations of chemicals, dissolved oxygen, biochemical oxygen demand, specific conductance, pH, and fecal coliform. The type and intensity of forest management practices will affect these water quality parameters differently. The forest practices with the greatest potential for causing erosion and stream sedimentation are road construction, tractor skidding of logs, and intensive site preparation (Stednick, 2000).

Clearcutting is the most intensive among forest harvesting practices, and its adverse affects on water quality are the greatest. Clearcutting northern hardwoods in New Hampshire caused a 50-fold and 10-fold increase in NO3-and AL3+, respectively (Likens, 1977). Brown and Krygier (1970) reported an increase of 16°C and Woods (1980) observed a reduction in dissolved oxygen to 1.7 mg/L in northern California after a clearcut.

Some forest management practices include fertilization. This can degrade water quality if nutrients are allowed to enter the stream system. Fertilization normally takes place at stand establishment as a site preparation technique; this time represents the lowest evapotranspiration and highest runoff rates, thus greatest risk of contamination. Fertilization is also occasionally applied in mid-rotation. Fertilizer applied during this time period is not likely to affect water quality (Mckinney, 1996).

Forest Management and Stream Sediment

Stand management is done throughout a forest's life, prior to final harvesting. Burning and thinning of overstory, mowing, and herbicide application are all done to improve the wood quality or increase the growth of the desired trees. These techniques can alter evapotranspiration and runoff rates; however, these effects are short-lived due to regeneration. Any forest activity that reduces canopy cover and/or disturbs the forest floor has the potential to cause an increase in erosion and sediment yield in streams.

The techniques employed to harvest forest resources can affect the impact the activity will have on soil disturbance. In the Pacific Northwest, soil disturbance from a clearcut can range between 5% to 25% depending on extraction method. Lower disturbance is reported from aerial logging (overhead cables or helicopter), while more disturbance results from traditional rubber tired skidders (Satterland and Adams, 1992). In eastern Ontario low intensity harvesting utilizing horses has shown to be less invasive. In extreme cases (Swift, 1984), forest roads can account for 90% of all sediment production in forested watersheds. Erosion from roads is primarily a result of low permeability of road surfaces, concentrated overland flow via ditches, and the construction of stream crossings. Diverting runoff from the road surface to the forest (away from streams) and reducing road gradients are two primary measures employed to reduce sediment load in streams.

As discussed, timber harvesting increases the water yield of a watershed. Alternatively, reforestation can reduce the watershed's water yields. Watersheds that include agricultural areas that are seasonally void of vegetation, abandoned fields, remediated brownfields etc., can have water yields manipulated by the re-introduction of forested lands. These reforested areas will reduce the amount of runoff and increase evapotranspiration. Thus, reforestation can be a technique for reducing the volume of erosion entering a stream.

Location	Treatment	Erosion or sedimentation rate	Unit	Measurement	Reference
East					
Georgia Piedmont	Control	0.002	Tons/ac/yr	Sediment	Hewlett 1979
	Harvest	1.8	Tons/ac/yr		
	Roading	1.6	Tons/ac/yr		
North Carolina	Roller-chop and burn	1.8	Tons/ac/yr	Erosion traps	Pye and Vitousek 1985
	Shear stumps, windrow slash	1.8	Tons/ac/yr		
	Above plus herbicide (glyphosate)	4.5	Tons/ac		
Southeast United States	Natural	0 – .2	Tons/ac/yr	Erosion	Burger 1983
	Harvest with roads	.05 – .23	Tons/ac/yr		
	Burn	.02 – .32	Tons/ac/yr		
	Chop	.02 – .11	Tons/ac/yr		
	Chop and burn	.07 – .18	Tons/ac/yr		
	Windrow slash	.09 – .11	Tons/ac/yr		
	Disk	1.13 – 4.5	Tons/ac/yr		
Coweeta Hydrologic Laboratory, NC	Poor road design	840	Yd^3/mi of road	Volume/road length	Swift 1988
	Poor road design	5700	mg/L	Sediment conc.	
	Good road design with grass or gravel	.02 – .3	Tons/ac		
Hubbard Brook Experimental Forest, NH	Natural (WS4-WS6)	.011	Tons/ac/yr	Erosion	Hornbeck and others 1987
	Harvest and herbicide	.05	Tons/ac/yr		
Fernow Experimental Forest, WV	Natural	.05	Tons/ac/yr	Erosion to stream	Aubertin and Patric 1972, 1974
	Harvest	.02	Tons/ac/yr		
Cherokee County, TX	Natural	.008	Tons/ac/yr	4-yr average	Blackburn and others 1986
	Harvest, chop, and burn	.006	Tons/ac/yr		Blackburn and Wood 1990
	Harvest, shear, windrow, and burn	.36	Tons/ac/yr		
Natchez, TN	Control	82	mg/L	Stormflow sediment concentration	McClurkin and others 1985
	Harvest only	183	mg/L		
Gulf coastal Mississippi	Control	0.2	Tons/ac/2 yr	Erosion over 2 yr	Beasley 1979
	Harvest, chop, and burn	6.7	Tons/ac/2 yr		
	Harvest, shear, and windrow	6.7	Tons/ac/2 yr		
	Harvest, shear, and windrow and plow beds	9.0	Tons/ac/2 yr		

Table 10: Effects of various timber harvests or site preparations on soil erosion and sediment production. (Stednick, 2000)

Site preparation techniques may also increase water yields. Burning, disking, piling of debris, and other techniques are used to make the replanting of a harvested area easier. These techniques smooth the land surface, causing greater runoff velocity and less infiltration (Mckinney, 1996). Forest cutting and site preparation are intensive activities that can result in great volumes of erosion. The erosion rates will vary depending on the site preparation method (burn, chopped, disked, etc.). A study in east Texas (Chang and Ting, 1986) showed very different surface runoff and sediment generation results under different forest site conditions. Under full forest cover, sediment production was limited to 1.4 kg/ha after two consecutive storm events (17.65cm and 0.98cm) over approximately 24 hours. The site that was clearcut and subsequently tilled produced 1250 kg/ha of sediment.

Variable	Undisturbed Mature Forest	Thinned Forest (50%)	Commercial Cutting w/o Site Prep.	Clearcut (Note 1)	Clearcut (Note 2)	Clearcut (Note 3)
Rainfall (cm)	14.58	15.32	17.45	18.63	18.63	18.63
Runoff (cm)	1.26	1.40	1.45	3.82	5.47	15.49
Sediment (t/ha)	0.0014	0.0011	0.0051	0.0965	0.3412	1.2504

Notes
1. roller chopped
2. sheared, root raked, slashed, and windrowed
3. tilled, continous fallow, cultivated uphill and downhill

Table 11: Surface runoff and sediment generated from two consecutive storms under six forest site conditions near Nacogdoches, Texas. (Adapted from Chang, 2003)

Forest Roads and Water Quality

When an area is harvested, temporary or permanent logging roads are constructed; they can capture subsurface flow and divert it to ditches associated with the road (Mckinney, 1996). These roads can also increase surface flow that would ordinarily be dispersed and infiltrate (Satterlund and Adams, 1992). Because of the surface characteristics of roads, precipitation that falls on them has a reduced capacity to infiltrate. In the Canaan River watershed in New Brunswick, the Fundy Model Forest (2003) observed soil disturbance resulting from land use practices. The main cause of change in lake water quality was increased silt deposition from three sources: commercial forestry operations (especially the roads associated with these operations) in the lake's upper watershed; construction of access roads; and land-clearing associated with increased recreational use of shores. As much as 90% of all sediment produced from forests could originate from forest roads and stream crossings (Megahan, 1972; Grace, 1999).

Forest roads expose ground surfaces to accelerated erosion and vehicle impacts. They also disrupt watershed drainage patterns and increase overland flow speed and momentum. Sediment production is greater on roads built in areas characterized by steep slopes, unstable topography, floodplains, and plentiful precipitation. There are many types of structures used to cross streams (e.g. bridges, culverts, logs, fords). Fords are the worst stream crossing type when conducting forest harvesting (Taylor, 1999) in terms of promoting stream sediment. In a 25 year study conducted in the H.J. Andrews Experimental Forest in Oregon it was observed that despite forest roads only comprising 5% of the watershed area, they contributed 51% of the annual soil erosion losses. The volume of soil eroded from roads was 30 times the volume removed from an undisturbed forest, and 10 times the volume from a clearcut in the same study area (Mersereau and Dryness, 1972).

Stream habitat can be impaired by additional sediment induced by forest practices. Most forested streams have less than 10 mg/L of sediment under normal conditions, and up to 100 mg/L under storm events (Binkley and Brown, 1993). After intense forest harvesting in northern Mississippi sediment loads were recorded at 14,949 mg/L. Increased sediment can alter channel morphology (Chamberlin, 1991), reduce benthic invertebrate populations (Newcombe and MacDonald, 1991), and degrade substrate quality important for fish spawning (Waters, 1995).

Location	Vegetation	Treatment	Sediment mg/l	Sediment JTU	Measure	Reference
Bull Run, OR	Conifers	25% cut, roads, burned	2,600		Maximum	Harr and Fredriksen, 1988
		Control	2–6		Range	
Alsea, OR	Douglas fir	100% cut, burned	20–7,670		Range	Brown and Krygier, 1971
		Control	32–256		Range	
H/J Andrews Experimental Forest, OR	Douglas fir	25% patch cut/road	1,850		Maximum	Fredriksen, 1970
		Control	8		Maximum	
Entiat Experimental Forest, WA	Firs, pines	Below road construction	497		Peak in July	Fowler et al., 1988
		Control (above)	4			
Chiachagof Island, AK	Sitka spruce	Logged/burned	1,268		Maximum	Stednick et al., 1982
		Control	313		Maximum	
Parsons, WV.	Hardwoods	Commercial cutting		56,000	Maximum	Reinhart et al., 1963
		Control		15	Maximum	
Leading Ridge, PA	Hardwoods	Commercial cutting		550	Maximum	Lynch et al., 1975
		Control		25	Maximum	
Hot Springs, MS	Shortleaf pine	Cutting/roads/yarded	6,000		Dec. 1983	Ursic, 1991
			556		5-year mean	
		Control	67		5-year mean	
Northern Mississippi	Loblolly pine	Sheared/bedded	14,949		Max. month	Beasley, 1979
			1,260		1-year mean	
Alto, TX	Southern pines	Sheared	2,119		1-year mean	Blackburn et al., 1986
		Control	90		1-year mean	

Table 12: Effect of forest practices on suspended sediments. (Chang, 2003)

Riparian Forest Buffers

Buffer strips or buffers are one of the most effective practices to inhibit sediment from entering a stream, river or lake. A buffer refers to an area that is managed in order to reduce the impacts of land use. A riparian forest buffer is therefore a combination of the two terms and refers to a forested area between water and land that is managed in order to maintain the hydrological and ecological well being of the channel and the shoreline. Riparian forest buffers have many functions including: controlling runoff, filtering and converting sediments, filtering nutrients and other chemicals, and providing an abundant habitat for fish and other aquatic wildlife (Alliance for the Chesapeake, 1996).

Newbold (1980) discusses the effectiveness of buffer strips. In a study of 50 streams in northern California, those streams with buffer strips of 30m or more, exhibited macroinvertebrate diversity levels the same as the control streams (no forest harvesting). Streams without the buffer showed considerably lower biodiversity. Buffer strips require a width greater than the distance sediment can travel downslope. This travel distance is controlled by slope, overland flow velocity, particle size and surface roughness. As one might expect the width necessary could vary greatly between sites. Recommended widths vary between 10-100 metres. Swift (1986) suggests two site specific equations for determining buffer strip width. For graded gravel roads without brush barriers in the southern Appalachians, the following equation can be used to determine the necessary set back: SMZ = 13 + 0.42 S, where S is slope in percent. If brush barriers do exist the equation is reduced to SMZ = 10 + 0.12 S. For a 30% slope these equations suggest buffer strips of 26 metres and 14 metres for no brush barriers and brush barriers respectively. Steinblums (1984) suggests that buffer strips be wider in wind prone areas to discourage windthrow.

Riparian cover is very important for aquatic habitat. Streams under overhanging vegetation have cooler water and air temperatures in the summer and warmer in the winter. Furthermore, the removal of riparian vegetation generally stimulates primary production by microbial communities, algae, and invertebrates (Gregory, 1987). This, in turn, increases decomposition rates of organic matter which may lead to deficiency of organic matter and decreased dissolved oxygen (causing stress and even mortality in fish). Streams have more nutrient input and aquatic life as a result of the sheltering/protection vegetation affords. Shading and sheltering effects can be provided by vegetation in many forms, including streamside or submerged vegetation, logs, and floating debris (Bjornn and Reiser, 1991). Cunjak and Power (1987) reported that both brook and brown trout prefer submerged cover structures in comparison to above-water structures in southern Ontario.

Forestry practices have potential impacts on stream habitats and aquatic communities by: altering the structure and composition of riparian vegetation, allowing more solar radiation to reach stream surfaces, and generating more stream sediment to the stream channel, and decreasing the amount of large woody debris (LWD) (Chang, 2003).

The removal of riparian vegetation can affect the food supplies for the stream. Cutting riparian vegetation will reduce the supply of leaves, needles, twigs and wood to the stream. By altering the composition of the riparian area, the organic matter can be altered (e.g. change from decay-resistant coniferous material to more readily decomposable deciduous matter). Removal of vegetation will reduce the volume of insect and animal waste dropping from the canopy into the stream.

Omernick (1981) questioned whether it is the presence of forested buffers or the presence of forest in general that contributes to improved water quality. His study compared 80 watersheds with varying amounts of forested and agricultural land. They found that nutrient concentrations in streams could be predicted by the percent of land cover in forest or agriculture, but there was no significant relationship between the proximity of the forest to the stream. The study suggests that as the amount of forest cover in the watershed decreased from more than 75 percent to less than 25 percent of the watershed, there was a corresponding increase in nitrogen and phosphorus concentrations in streams, regardless of whether the forest was located adjacent to or away from the stream itself.

Nutrient Loading

Nutrients are essential elements for aquatic life; however, in excess, they can lead to negative changes in the aquatic ecosystem and reduce the quality of water. Nutrients contained in plant materials or naturally eroding soils are natural inputs into a stream. Many unnatural nutrients such as fertilizers, sewage, and manure are present in large concentrations in surface water. Industrial sources and atmospheric deposition also contribute significant amounts of nutrients. Agricultural lands are a large source of nutrient (primarily nitrogen and phosphorous) inputs into streams. On a per-acre basis, intensive livestock operations (such as feedlots) release more nutrients into the environment than other agricultural activity such as row crops, small grains, or pasture (Beaulac and Reckhow 1982).

Nutrients can enter surface waters in a dissolved form or attached to soil particles via both throughflow and overland flow. For example, nitrogen is most commonly transported as dissolved nitrogen through subsurface flows, with peak nitrate levels occurring during the dormant season after crops have been harvested and soil evaporation rates are reduced. In contrast, phosphorus most often enters the stream absorbed into soil particles and organic materials in surface runoff after storm events. Probably the most significant impact of nutrients on streams is eutrophication - the excessive growth of algae and other aquatic plants in response to high levels of nutrient enrichment (U.S. E.P.A. 1995). Increased aquatic plant life results in lower dissolved oxygen, increased volumes of decaying organic matter, undesirable color, taste, and odor. Some algae may also form toxins which are directly harmful to aquatic organisms and humans. Riparian forests have been found to be effective filters for nutrients, including nitrogen, phosphorus, calcium, potassium, sulfur, and magnesium (Lowrance, 1984).

Nitrogen

Riparian forests remove nitrogen from agricultural runoff. A study in Tifton, Georgia observed that deciduous forest buffers reduced nitrogen from agricultural runoff by 68 percent (Lowrance, 1984). On the western shore of the Chesapeake Bay in Maryland, scientists estimated a riparian buffer removed 89 percent of the nitrogen from field runoff, mostly in the first 62 feet of the buffer (Peterjohn and Correll 1984). In the Nomini Creek watershed, near Richmond, Virginia, forested riparian buffers reduced concentrations of nitrate-nitrogen in runoff from croplands by 48 percent (Snyder and others 1995).

Nitrate reduction is greatest in riparian forests with a high water table and highly organic soils. In Wisconsin, it was observed that nitrogen levels were reduced most in the areas of the riparian forest that were frequently flooded; nitrogen levels remained high in drier areas of the buffer (Johnston and others 1984). Nitrate removal rates were as much as 70 percent higher when the water table was within 20 inches of the soil surface. (Gold and Groffman 1995). It was also shown that there was little seasonal variation in the nitrate removal capacity of a riparian buffer. The highest rates occurred during the dormant season. Furthermore, the studies showed that the availability of carbon was a limiting factor in nitrate reduction. Cooper (1990) found that where throughflow occurred in organic soils prior to entering streams, nitrate levels were reduced 100 percent; however, mineral soils exhibited little capacity to decrease nitrogen.

These results support the hypothesis that the primary mechanism for nitrate removal by riparian forests is denitrification. Denitrification is a process whereby nitrogen in the form of nitrate, NO_3^- is converted to gaseous N_2O and N_2 and released into the atmosphere. Denitrification permanently removes nitrogen from the riparian area because nitrates are converted to nitrogen gas and released to the atmosphere.

Plants absorb large quantities of nitrogen as they produce roots, leaves, and stems; however, the majority of this is returned to the soil as plant materials decay. In Maryland, it was estimated that deciduous riparian forests took up 69 pounds of nitrogen per acre annually, while returning only 80 percent each year in the litter (Peterjohn and Correll 1984). Trees in particular remove nitrates from deep in the ground; convert the nitrate to organic nitrogen in plant tissues, and then deposit the plant materials on the surface of the ground as litter, where it is denitrified by soil microbes. It is clear that the removal of nitrogen through dentrification relies on more than vegetation; it requires certain soil and hydrological conditions, including soil texture, organic matter content, and groundwater flow paths (Speiran, 1998).

Phosphorous

Riparian areas can help protect water courses from phosphorus loading. They are generally less effective in removing phosphorus than either sediment or nitrogen (Parsons, 1994). The primary mechanism for phosphorus removal by riparian buffers is the deposition of phosphorus associated with sediments. Cooper and Gillian (1987) found that half the phosphorus entering a riparian forest in North Carolina was deposited within the forest. Others have reported a 30-80 percent reduction in particulate phosphorous from agricultural areas by hardwood forests (Lowrance, 1984, Peterjohn and Correll, 1984).

Dissolved phosphorus may also be removed from runoff waters through adsorption by clay particles, particularly where there are soils containing clays with high levels of aluminum and iron (Cooper and Gilliam, 1987). This has led some (Walbridge and Struthers, 1993) to believe that riparian areas are particularly good at capturing dissolved phosphorous because clays tend to accumulate in riparian soils. Unlike nitrogen, Walbridge and Struthers (1993) suggest phosphorus absorption is reduced in soils with high organic matter. Phosphorus is used by vegetation and soil microbes, but like nitrogen, 80-97% is eventually returned to the soil as litter (Brinson, 1984, Peterjohn and Correll, 1984).

Pathogens and Toxins

Riparian forest buffers slow the movement of contaminants such as pathogens and toxins to surface waters and increase the opportunity for the contaminants to become buried in the sediments, adsorbed into clays or organic matter, or transformed by microbial and chemical processes (Johnston, 1984).

Pathogens such as waterborne bacteria, viruses, and protozoa can enter streams and lakes from various sources: sewage, wildlife, storm runoff, septic systems, and livestock operations. Pathogens can survive longer if they become adsorbed into sediments or organic matter (Palmateer, 1992). High nutrient levels and turbidity in the water also increase survivability of bacteria by providing a source of nutrition and reducing the amount of sunlight which penetrates the water (UV light can kill bacteria). There have been no studies that discuss the ability of riparian forest buffers to reduce contamination by pathogens; however, a few studies looked at the effect grasses and crops can have. Young (1980) found that strips of corn, oats, orchardgrass, and sorghum/sudangrass were all effective in reducing fecal coliform bacteria levels (runoff from a cattle feedlot) by nearly 70 percent. Larsen (1994) found that 2 and 7 foot strips of grass sod removed 83 and 95 percent of the fecal coliform bacteria running off dairy cow manure, respectively.

Chemicals with adverse and long-term effects are referred to as toxins. Toxic pollutants can affect aquatic organisms by increasing their susceptibility to disease, interfering with reproduction, causing adverse physiological effects, and causing behavioural changes. In humans, toxins have been shown to cause disorders of the immune, reproductive, developmental, and neurological systems. The toxins of greatest concern in aquatic systems are pesticides and metals. Pesticides are used primarily in agricultural areas; however they are also commonly used on golf courses, urban lawns and gardens, and in plant nurseries.

Pesticides can enter streams either in a dissolved state, attached to soil particles, or deposited through the atmosphere. Riparian forest buffers have the potential to remove and detoxify pesticides in runoff. Soil microorganisms adapt to the presence of a pesticide and begin to metabolize it as an energy source, ultimately resulting in carbon dioxide (Fausey, 1995). Most pesticides have a high affinity for clay and organic matter, and may be removed from the soil water as they are bound to soil particles (Clapp, 1995). Studies have been conducted on the ability of grass filter strips to reduce pesticide levels from agricultural sources. Results are variable depending on the pesticide being tested. For example, an herbicide called trifluralin from agricultural runoff was reduced between 86-96 percent by grass filter strips in southern Georgia (Rhode, 1980). About half of the herbicide was adsorbed onto vegetation or organic matter, while soil infiltration accounted for one-third. Adsorption of pesticides seems to be greatest in soils with high organic matter.

In eastern Ontario, industrial processes, urban runoff, transportation activities, agricultural pesticides and fertilizers can release metals into aquatic environments. Metals are a unique threat because they do not degrade; they tend to accumulate in stream sediments; and they may accumulate in plant and animal tissues. The fate of metals in riparian areas is not well understood; however, studies have shown that sediments and woody tissues in trees can trap and uptake (respectively) metals such as lead, chromium, copper, nickel, zinc, cadmium, and tin (Hupp, 1993). Therefore, sediment deposition and uptake by woody vegetation may help mitigate heavy metal accumulation in water adjacent to riparian areas.

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