CHAPTER 2: PHYSICAL CHARACTERISTICS OF *SPHAGNUM*-DOMINATED PEATLANDS IN WESTERN WASHINGTON

Ranging from tidal flats and low elevation sand dunes to the foothills of the Cascade Mountains, the topography of western Washington encompasses a great diversity of landforms and parent materials. The landforms in this area provide a variety of opportunities for peatland development, varying with the topography and physiography. An ideal framework in which to discuss the physical characteristics of western Washington peatlands is that of physiographic regions, covered in the first section of this chapter. Next descriptors of western Washington climate and rainfall are given, and a summary of the role of climate in peatland formation is provided. Lastly, some characteristics of western Washington *Sphagnum*-dominated peatlands and their watersheds are presented, followed by a general discussion of developmental pathways and isolating mechanisms in peatlands.

2.1 Physiography and Distribution

A number of authors have described the Washington area, developing their own system of physiographic regions, also called provinces (Easterbrook and Rahm 1970; Fenneman 1931; Franklin and Dyrness 1973; Hansen 1947; Rigg 1958). This has resulted in similar systems with slightly different regional names and boundaries. This paper will follow those established by Rigg (1958), although other sources will be used to supplement descriptions where regions are similar.

Of the seven physiographic regions defined by Rigg for Washington State, four can be found within western Washington. These four provinces, the Olympic Mountain, Puget Sound, Willapa Hills and Cascade Mountain, contain the majority of Washington's peatlands. These four main western Washington provinces contain 82% by area and 84% by number of the state's peat resources, as identified by Rigg (1958). Although the 84% figure includes some peatlands from higher elevations above 609 m (about 2000 feet), they are not part of this inventory. Since the majority of peatlands are located in western Washington, sound management and preservation of these peatland ecosystems is critical to maintaining the peatland natural heritage for the entire state.

The Olympic Mountain physiographic province is bounded to the north by the Strait of Juan de Fuca, to the west by the Pacific Ocean, to the east by Puget Sound, and to the south by the Chehalis River valley (Easterbrook and Rahm 1970). It consists of coastal lowlands skirting the Olympic Mountains. The Olympic peaks rise to elevations of 1800 to 2100 meters (5,904 to 6,888 feet) with the tallest, Mt. Olympus, reaching 2424 meters (7,951 feet) (Easterbrook and Rahm 1970), but elevations over 610 m (about 2000 feet) are not part of this profile area. The lowlands are thought to be an uplifted coastal plain which slopes towards the coast, and is generally less than 120 meters (394 feet) in elevation (Fenneman 1931). As described by Rigg (1958), the Olympic Mountain province consists of both the coastal lowlands and the central mountains, with the exception of the lowland regions to the east, north-east and south-east of the peninsula, which are included in the Puget Sound province (Rigg 1958). Because of this distribution pattern, the average elevation of *Sphagnum*-dominated peatlands in the Olympic

Mountain physiographic province is lower than that of the *Sphagnum*-dominated peatlands in the Puget Sound province (see Table 2-1). Seventeen per cent of the *Sphagnum*-dominated peatlands in this western Washington inventory are in this physiographic province (see Table 2.2).

TABLE 2.1 Minimum, maximum and average elevations of *Sphagnum*-dominated peatlands in the physiographic provinces of western Washington.

Physiographic Province	Elevation meters (feet)[1]			
	Minimum	Maximum	Average	Number in sample
Cascade Mountain	108 (340)	542 (1,780)	300 (986)	23
Puget Sound	1.5 (5)	360 (1,180)	114(374)	163
Olympic Mountain	3 (10)	366 (1,200)	105 (346)	42
Willapa Hills	8 (25)	49 (160)	26 (84)	5

[1] Elevations are rounded to the nearest meter or foot.

TABLE 2.2 Number of *Sphagnum*-dominated peatlands by physiographic province.

Physiographic Province	Sphagnum-dominated peatlands	
	Number	Percent of total
Puget Sound	176	71
Olympic Mountain	43	17
Cascade Mountain	23	9
Willapa Hills	5	2
Total	247	100

All of the sites identified as part of the Olympic Mountain physiographic province fall within Hansen's (1947) coastal strip natural area. The vegetation of the western lowland strip along the Pacific Ocean is also quite distinctive, comprising the Sitka spruce (*Picea sitchensis*) forest zone, while all other regions of western Washington are part of the Western hemlock (*Tsuga heterophylla*) forest zone (Franklin and Dyrness 1973). This low elevation strip of Sitka spruce forest also continues southward along the coast, extending into the Willapa Hills physiographic province of Rigg (1958). Figure 2.1 (adapted from Kunze, 1994) includes the Olympic Mountain province as well as the Willapa Hills province, which is in southwestern Washington.

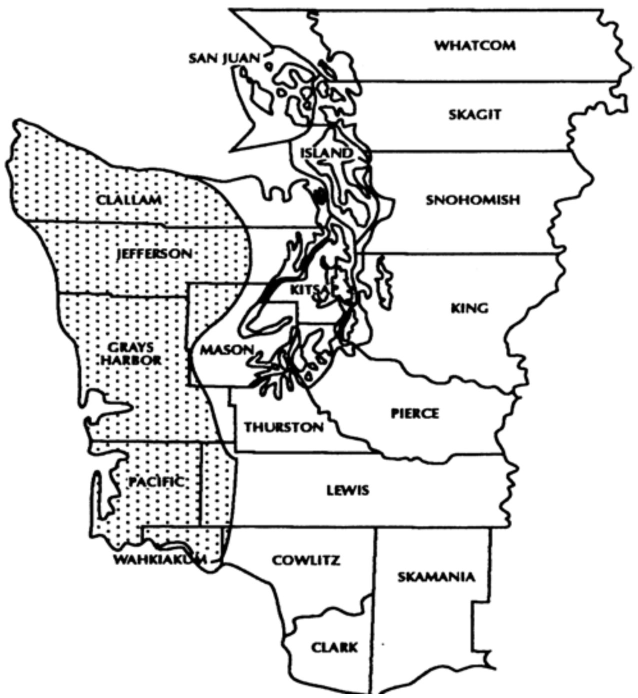

FIGURE 2.1 Olympic Penninsula and Willapa Hills Physiographic Provinces.

The Puget Sound physiographic province contains the majority of western Washington peat deposits identified by Rigg. It occupies the lowland areas surrounding Puget Sound and foothills of the Cascade Mountains, the western border abutting the lower hills of the Olympic Mountains in the northwest and the Willapa Hills in the southwest (see Figure 2.2). The Cowlitz River valley and the upper basin of the Chehalis River occupy the southern regions of the province (Fenneman 1931). The northern portion of the basin, which drains to Puget Sound, is separated from the Chehalis and Cowlitz drainages by a terminal moraine, representing the southern limit of the Wisconsin ice sheet (Hansen 1947). Thus the topography of the northern Puget Sound province is a consequence of glaciation, while that of the more southern part of this region is primarily a result of stream erosion (Easterbrook and Rahm 1970).

The Puget Sound region is an area of low relief, having elevations of less than 150 meters (492 feet), with only a few exceptions (Fenneman 1931). *Sphagnum*-dominated peatlands in this region ranged in elevation from 1.5 meters (5 feet) at Cranberry Lake on Whidbey Island to 360 meters (1,180 feet) in eastern Skagit county. Elevation data are available for only 163 of the 180 identified peatlands in this physiographic region.

Glaciation in the Puget Sound province favored the formation of several types of glacial lakes, many of which have filled with organic sediment, or are in various stages of lake-fill succession (Hansen 1947). In contrast, south of the terminal moraine just south of Olympia, the province contains fewer areas of standing water suitable for peat formation (Hansen 1947). Only one of the 176 *Sphagnum*-dominated peatlands identified in the province occurs south of the terminal moraine. Because of the favorable topography and infertile soils in the glaciated basin, the province contains the majority, or 71% of the *Sphagnum*-dominated peatlands identified in western Washington. Table 2.2 presented the number of *Sphagnum*-dominated peatlands identified in this study for each physiographic province.

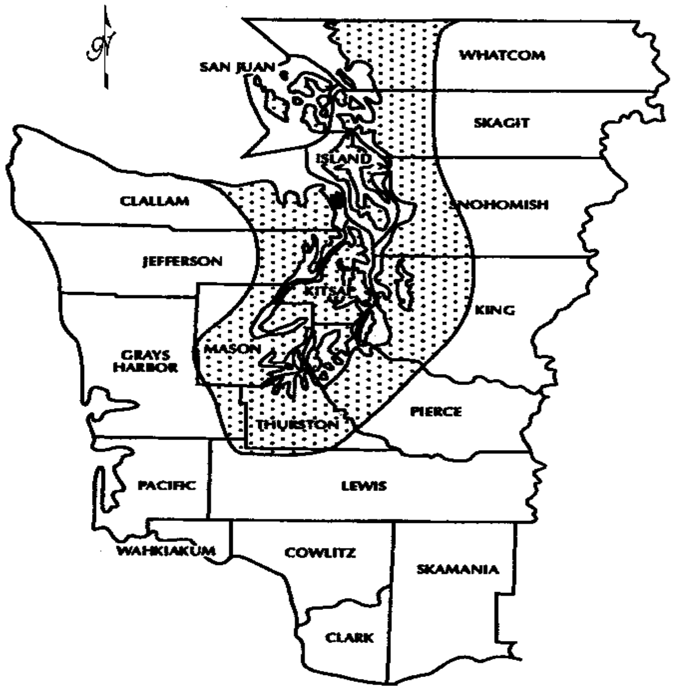

FIGURE 2.2 Northern portion of the Puget Sound physiographic province.

The **Willapa Hills Physiographic Provinces** is considered the northern extent of the Oregon Coast Range by Fenneman (1931), and lumped with the Coastal Strip natural area by Hansen (1947), as depicted in Figure 2.1. It occupies the region between the Pacific Ocean and the Puget Sound physiographic province south of the Chehalis valley and north of the Columbia River (Easterbrook and Rahm 1970; Rigg 1958). As the name suggests, the region is hilly, reaching elevations of approximately 500 to 900 meters (1640 to 2,950 feet) (Easterbrook and Rahm 1970), although most of the area is less than about 500 meters (1640 feet) (Rigg 1958). Containing only five known *Sphagnum*-dominated peatlands, this province has minimal importance in terms of area or volume of *Sphagnum* peat deposits. The nature of these deposits is quite different from other deposits in western Washington. Areas of sand dunes are prevalent along the coastal regions, just north of the mouth of the Columbia River, as well as north of Willapa Bay (Rigg 1958). It is in these dune regions that four of the five *Sphagnum*-dominated peatlands identified in this province occur. All four are found as scattered patches of *Sphagnum* in large wetland complexes, estimated at 8,000 to 16,000 hectares (about 19,700 to 39,500 acres) by Rigg (1958), and occur in the elongated depressions between sand dunes. Only one peatland occurs outside of ocean beach sand dune complexes, at 50 meters (164 feet) elevation.

The **Cascade Mountain physiographic province** extends westward from the eastern border of the Puget Sound physiographic province. Like the Puget Sound province, the Cascade Mountain physiographic province extends from the Canadian border, south to the Columbia River, which forms the border with Oregon State (Rigg 1958). Most of the peaks and ridges of the Cascades owe their sharp detail to glaciation (Fenneman 1931), as do the many small lake basins present in the province (Hansen 1947). These montane glacial lakes are generally shallower than those forming on glacial drift from continental ice sheets, and, as a result, the organic sediments within them are thinner (Hansen 1947). There are exceptions to this, with several peat deposits reaching depths comparable to lower elevation peatlands (Hansen 1947). According to Rigg (1958), some deposits are known to reach depths greater than 14 meters (46 feet). The Cascade Mountains province occupies the highest elevation sites in western Washington. Peatland elevations in this province range from 108 meters (340 feet) in the

Columbia valley to 542 meters (about 1780 feet), near the elevation limit established for this profile (see Table 2-1). The mean elevation is about 300 m (986 ft). Depressions containing lakes or peat deposits are widely scattered (Hansen 1947), and only 9% of western Washington's *Sphagnum*-dominated peatlands occur in this region (Table 2-2).

2.2 Climate and Rainfall of Western Washington

The climate of western Washington is maritime and characterized by moderate precipitation and evaporation, and temperatures that are strongly influenced by the Pacific Ocean. Within the study area, the National Oceanic and Atmospheric Administration has recognized four climatic divisions, which seem to be based largely on zones of equal rainfall (isohyets) shown in Figure 2.3 (adapted from Kruckeberg, 1991). The isohyets are based on long-term averages of normalized data. These divisions are the west Olympic coastal, Northeast Olympic-San Juan, Puget Sound lowlands, and east Olympic-Cascade foothills. Most of the Willapa Hills physiographic province and lowlands within the Olympic Mountain physiographic province are within the west Olympic coastal climatic division. Small, eastern portions of the Willapa Hills physiographic province are within the east Olympic-Cascade foothills climatic division. By contrast, most of the Puget Sound physiographic province fits within the Puget Sound Lowlands climatic division. A small portion of the Puget Sound physiographic province falls within the rain shadow of the Olympic Mountains and is included in the northeast Olympic-San Juan climatic division.

FIGURE 2.3 Zones of equal rainfall, western Washington area, in inches.

Precipitation, evaporation, and temperature data for these climatic divisions are described below based on reported data for four climate stations within each division except for the Northeast Olympic-San Juan division, which reflects data for only three climate stations. Evaporation data are available only for a climate station in the Puget Sound climatic division. It is likely that evaporation is lower in the west Olympic Coastal, east Olympic-Cascade foothills, and Willapa Hills climatic divisions, which are characterized by somewhat lower average monthly and annual temperatures. A summary of these data is presented in Table 2.3 and all data are in Appendix C, Chapter 2.

West Olympic Coastal

Coastal areas within the Olympic Mountain and Willapa Hills physiographic provinces have relatively high average annual rainfall. Average annual rainfall records for the 30-year period from 1961 to 1990 reported for Naselle, Neah Bay, Quillayute, and Aberdeen, show that rainfall varies from 2,032 to more than 2,921 millimeters (80 to 100 inches). About 85% of total precipitation occurs as rain between October and March. At least some precipitation falls each month. Snow occasionally falls in this area but rarely remains on the ground for more than a few days and is typically an insignificant amount of the monthly and annual total. Table 2.3 summarizes annual precipitation data for the four climatic divisions.

Average temperatures in the west Olympic coastal climatic division are relatively cool for much of the year. Temperatures range from a low of around 4ºC (39.9ºF) in winter (January) to a high of about 16ºC (61.2ºF) in summer (August). Average annual temperature in the west Olympic coastal division is about 10ºC (50.5ºF). Average annual precipitation and temperature data are summarized in the climate diagram for this division (see Figure 2.4).

TABLE 2.3 Average annual precipitation (mm, inches) and temperature (ºC, °F) data for climatic divisions.

Division	Average Annual Precipitation		Monthly evaporation (mm)+
	(mm)*	(inches)	
West Olympic Coastal	2580	101.59	
Puget Sound Lowlands	1096	43.14	18 -142
Northeast Olympic-San Juan	697	27.44	
East Olympic-Cascade Foothills	1500	59.05	
Division	Temperature		
	(°C)	(°F)	
West Olympic Coastal	9.8	49.7	
Puget Sound Lowlands	10.6	51.1	
Northeast Olympic-San Juan	9.9	49.9	
East Olympic-Cascade Foothills	10.3	50.5	

* 1961-1990 averages for all but one climate station in the northeast Olympic-San Juan and West Olympic Coastal divisions are based on normalized data.
+ 1966-1995 average

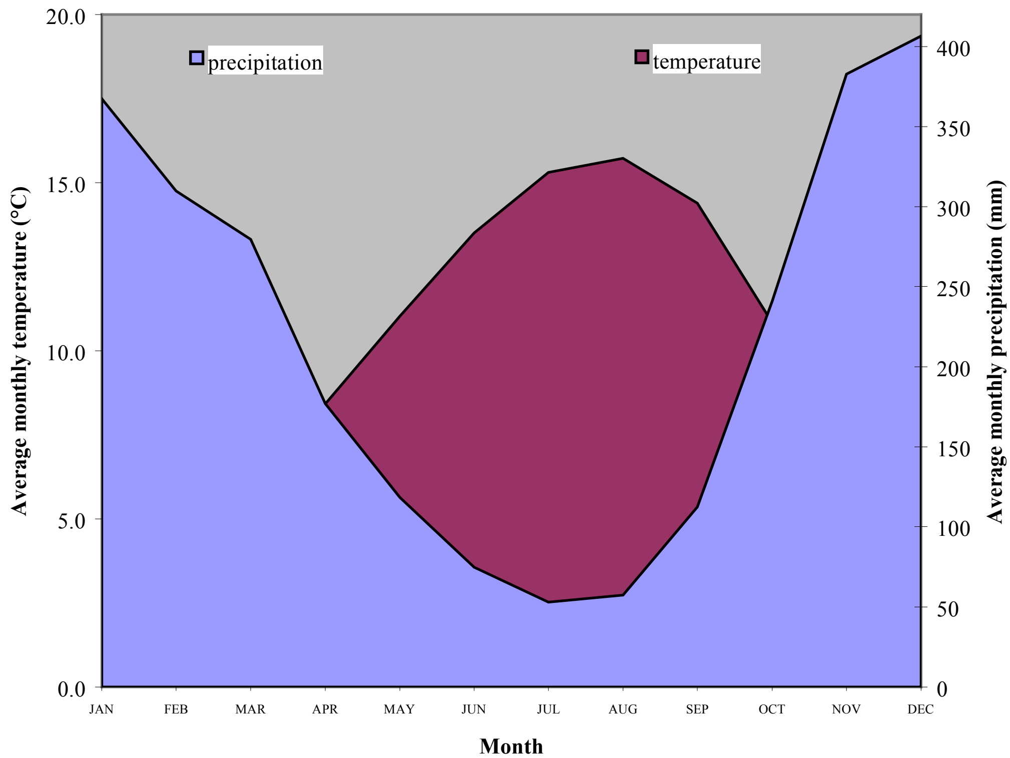

FIGURE 2.4 Climate diagram for West Olympic coastal areas.

Puget Sound Lowlands

Most of the Puget Sound province falls within this climatic division. Climate data collected at Monroe, Puyallup, Seattle-Tacoma International Airport, and Sedro Woolley are representative of the precipitation in this area. Average annual rainfall at these locations ranges from about 902 to 1,232 millimeters (35.50 to 48.50 inches). Of the total average rainfall, 75% occurs during the fall and winter between October and March. A little less than 5% of the annual precipitation is snow (Kruckeberg, 1991). Smaller amounts of rain occur in spring and during the summer drought, about 17% and 8%, respectively.

Average temperatures in the Puget Sound lowlands are somewhat higher than in the other climatic divisions but are still relatively cool. Average monthly temperatures for these climate stations range from a low of about 3ºC (38.3ºF) in January to a high of about 18ºC (65.5ºF) in the middle of summer (August). Average annual temperature in the Puget Sound lowlands is about 10 to 11ºC (50.4 to 52.0ºF).

Monthly average evaporation data are available for the Puyallup station for a 30-year period of record extending from 1966 to 1995, except for the months of January and December. Average evaporation data are lowest in winter and range from 18 to 40 millimeters (0.71 to 1.58 inches). During the spring

(April to June), average monthly evaporation rates increase to between 62 and 118 millimeters (2.46 and 4.63 inches). As might be expected, evaporation rates are highest during the summer months (July through September) and range from 74 to 142 millimeters (2.92 to 5.61 inches). In fall, evaporation rates decline to less than 33 millimeters (1.28 inches), assuming evaporation in November and December is lower than during the month of October. From May through September, evaporation rates are higher than precipitation rates based on data for the Puyallup station. Presumably this is also the case elsewhere in the Puget Lowlands, characteristic of areas that experience summer drought. For the rest of the year, precipitation exceeds evaporation, a condition typical in areas of peatland formation as will be discussed in the next section. Figure 2.5 shows a climate diagram of the precipitation and temperature data for the Puget Sound lowlands.

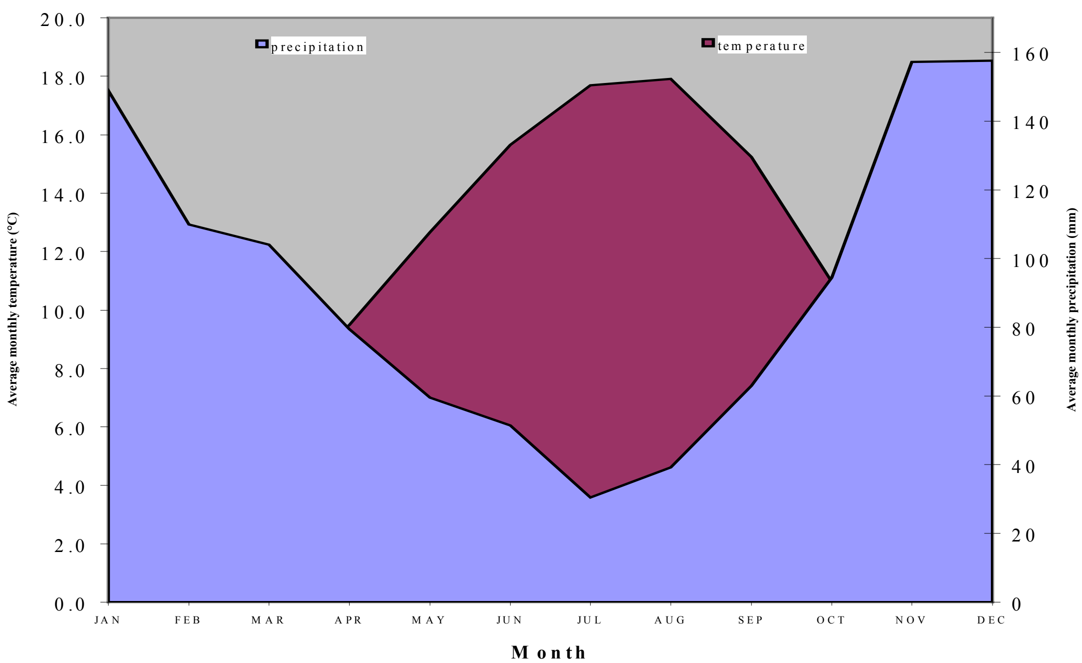

FIGURE 2.5 Climate diagram for Puget Sound lowlands.

Northeast Olympic-San Juan Islands.

Small portions of the Puget Sound physiographic province fall within this division. Average annual rainfall is lowest in this division, which lies within the rain shadow of the Olympic Mountains. Average rainfall varies from a low of 419 millimeters (16.51 inches) in the heart of the rain shadow at Sequim to 736 millimeters (28.98 inches) at Olga. This is about 18 to 64 percent lower than the other areas. These differences include lower amounts of precipitation during the summer drought as well as the wetter fall and winter months.

Average monthly temperatures are lowest in winter and highest in the middle of summer, and range from about 4 to 16ºC (39.5 to 61.4ºF). For the two stations in this division with temperature data, Coupeville and Olga, the average annual temperature was almost identical at about 10ºC (49.9ºF). There were no data for the Sequim climate station. Average monthly temperatures and precipitation are summarized in the climate diagram for this region (see Figure 2.6).

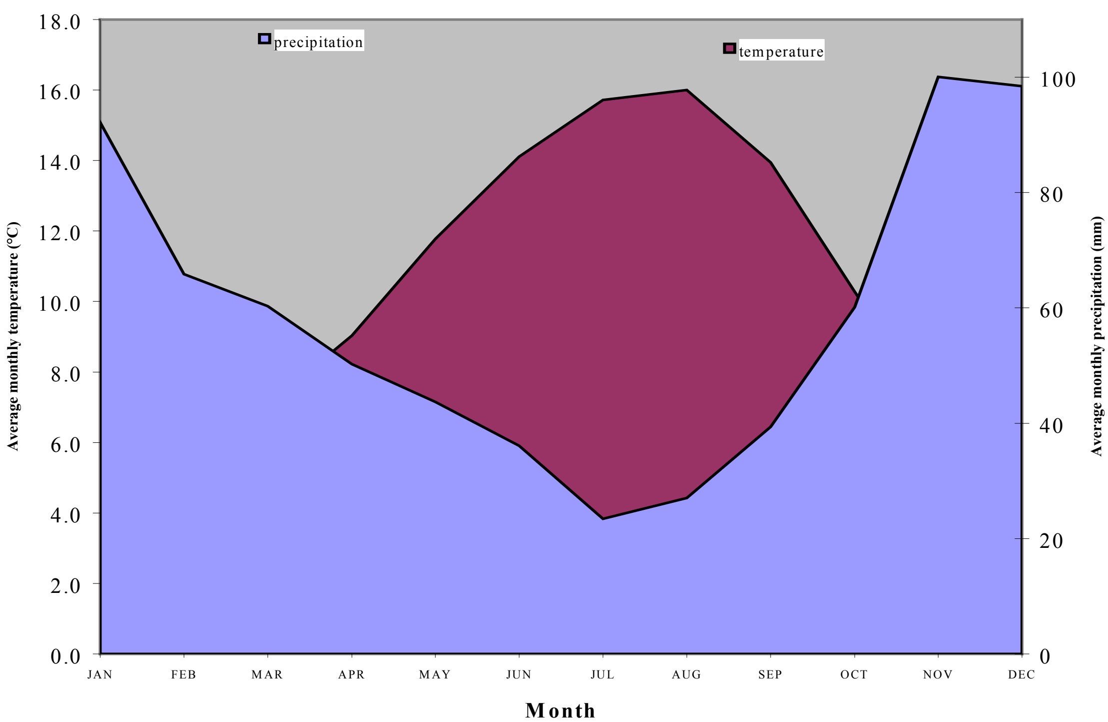

Figure 2.6 Climate Diagram for Northeast Olympic-San Juan Islands

East Olympic-Cascade foothills

This division includes portions of the Olympic Peninsula, Willapa Hills, and Puget Sound physiographic provinces. Average annual rainfall is lower than in the West Olympic coastal climatic division and higher than either the Puget Sound lowlands or Northeast Olympic-San Juan Islands divisions as indicated by average annual rainfall data for climate stations in Landsburg, Oakville, Quilcene and Shelton. For the 30-year period of record, average annual rainfall for these locations ranges from about 1,462 to 1,666 millimeters (57.56 to 65.60 inches). About 75% of the total average annual rainfall falls during the fall and winter between the months of October and March. Spring is drier, accounting for about 15% of the total average annual rainfall. About 10% of the total annual rainfall occurs during the summer drought (July through September). Temperatures are similar to the other divisions with a few notable exceptions. Average temperatures in December and January are somewhat lower for these climate stations than those reported for stations in the other divisions. This may be a reflection of the somewhat higher elevations at the Landsburg and Quilcene climate stations. In January, the lowest average monthly temperature for these stations is 2.9ºC (37.3ºF). The highest average monthly temperature for the period of record is 19ºC (65.3ºF) in August. Average annual monthly temperatures range from 10 to 11ºC (49.2 to 51.6ºF). Summer drought is likely to be less pronounced in the West Olympic Coastal and East Olympic-Cascade foothill climatic divisions, where average monthly precipitation is higher during the summer and average temperatures somewhat lower than in the other two western Washington climatic divisions. Lower temperatures are also likely to result in lower evaporation rates. Average monthly temperature and precipitation are summarized in Figure 2.7.

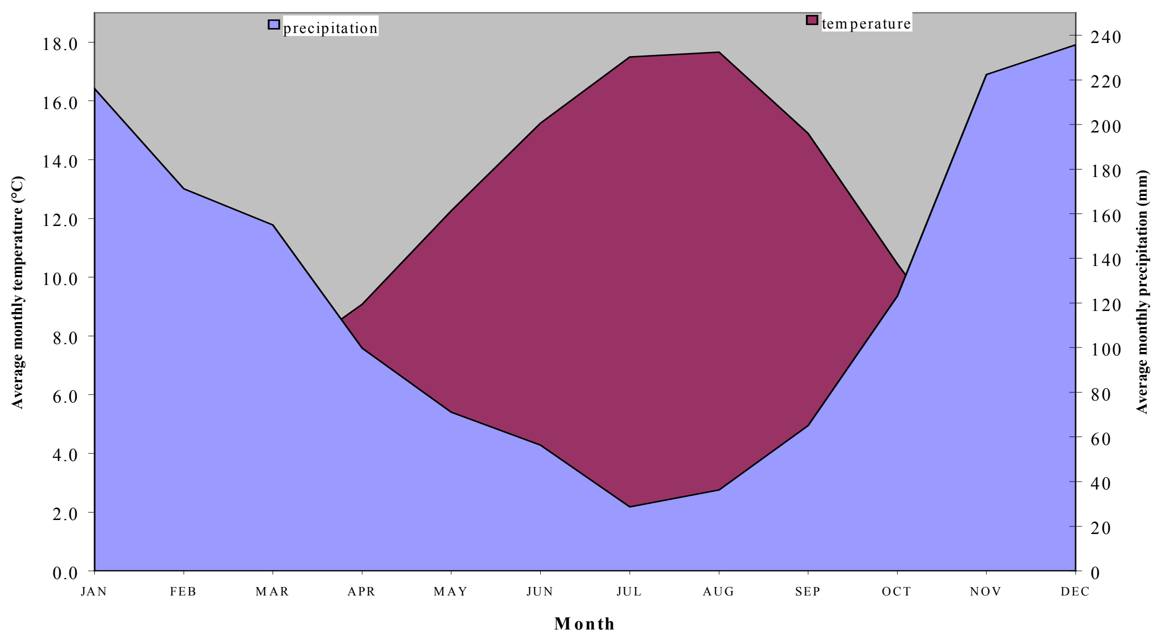

Figure 2.7 Climate Diagram for East Olympic-Cascade Foothills

2.3 The Role of Climate in Peatland Formation

Many authors have suggested that climate is a primary factor in the initiation and formation of *Sphagnum*-dominated peatlands. Climate also strongly influences developmental changes and successional trends. Vitt et al. (1994) and others (Rigg 1925; Osvald 1933) have indicated that bogs and fens develop where available precipitation exceeds evapotranspiration. These peatlands form when the annual water balance is positive and annual precipitation typically exceeds 500 mm. Such a climate clearly exists in western Washington. Regional differences between the climates within the different physiograhic regions in western Washington may explain differences in the *Sphagnum*-dominated peatland vegetation communities in the different physiographic provinces within the study area. Malmer (1986) observed that the flora of bogs in northwestern Europe that were influenced by oceanic climates have more permanent high water and shorter drought periods than continental bogs elsewhere in Europe. Malmer postulated that regional differences in the vegetation of European bogs were due to the hydrological variation that was climatically influenced rather than the atmospheric supply of minerals, as earlier proposed by Osvald (1949). There are insufficient data to determine what role either climate or atmospheric supply of minerals have on the composition of vegetation in *Sphagnum*-dominated peatlands in western Washington.

In addition to the role climate plays in peatland development, climate affects the fate of the peat itself. *Sphagnum* peat and other peat accumulates when primary production exceeds decomposition. Climate influences decomposition rates in peatlands by allowing saturated or anaerobic conditions to develop where drainage is poor. Since anaerobic decomposition proceeds at a much lower rate than aerobic decomposition, waterlogging leads to peat accumulation. Temperature also influences decomposition rates. Some authors (Engstrom 1984; Winkler 1988; Heinselman 1970) have suggested that reverse succession may occur as a result of changing climate. So, instead of a classical lake-infill succession culminating in a bog forest, peat decomposition may occur as a result of changes in water levels and small lakes with peaty margins may become larger lakes. It seems likely that lowering of groundwater or alteration of surface water hydrology resulting from development in the watershed of peatlands could also trigger such a reversal because anaerobic decomposition processes would be replaced by aerobic processes. Several peatland systems in western Washington appear to have experienced reverse succession from acidic peatlands to peatlands with water quality and vegetation more characteristic of rich fens or even the more typical shrub-dominated non-peat accumulating wetlands common in the region. Additional research is needed to document the causes of such changes and the thresholds at which such changes occur.

Peatlands, especially *Sphagnum*-dominated peatlands, can also influence temperature and ecological processes in nearby areas. As *Sphagnum* grows and *Sphagnum* peat accumulates, the living and dead tissues influence the microclimate of the peatland. Living *Sphagnum* affects decomposition rates by increasing acidity and depressing microbial communities. In addition, peat has very good insulating properties. As peat accumulates, it appears to affect microclimate, and the biological, physical, and chemical processes within peatlands. Fitzgerald (1966) conducted detailed studies of Kings Lake bog in King County, Washington. She established macro- and microclimate stations at various locations on the bog, which is located at an elevation of about 290 meters (950 feet), and in the adjacent upland forest. She found that the microclimate (at the surface) temperature maxima are higher and minima are lower in all of the bog vegetation zones (lake edge, inner bog, mid-bog, outer bog) compared to the upland forest. During the course of her investigation, she found that there were no frosts during the growing season in the adjacent forest, but frost occurred throughout the season in all vegetation zones on the bog. In addition, Fitzgerald (1966) found that the more mature and older parts of the bog exhibited more extreme temperatures than the younger parts, such as thin, floating mat adjacent to the lake edge. She concluded that tree seedling establishment and therefore forest succession may be prevented, or at least slowed, on the bog by extreme high summer temperatures that may cause heat lesions, and frosts (extreme low temperatures) that result in tree seedling mortality.

2.4 Characteristics of *Sphagnum*-dominated Peatlands in Western Washington

Information on the *Sphagnum*-dominated peatlands of western Washington has been compiled from multiple sources, each with different purposes. As such, the database for these peatlands contains information of varying detail and completeness. This makes it impossible to draw strong or definitive conclusions. Some general trends are apparent, but caution must be exercised in using this information. In many cases, trends are based on observations at only a few peatlands or on information collected by a variety of investigators with varying levels of expertise and differing primary purposes.

General

The entire Puget Sound physiographic province was glaciated, as well as portions of the Cascade and Olympic Mountain provinces. Many of the soils have developed on top of compact glacial till or coarser advance and recessional outwash deposits. These deposits often have relatively poor fertility and high winter water tables.

Rigg (1958) has estimated the age of western Washington peat deposits by dating the sedimentary peat forming the bottom of the peat profile. The average age when the accumulation of sedimentary peat began is about 12,000 year before present (b.p.). This corresponds with the retreat of the continental ice sheet in the Puget Sound Province (Foley, 2001). Using this date and the depth of 151 peat deposits, Rigg also arrived at an average rate of peat accumulation for western Washington. He found that on average it took 41 years to accumulate 2.5 cm (one inch) of peat, equivalent to an annual peat accumulation of 0.62 mm per year (0.02 inches). This is lower than estimates made by other investigators which range from 0.1 to 0.8 mm/year (Wieder et al. 1994). It should be noted, however, that peat accumulation rates are not thought to be constant. As evidence of this, an ash layer, common in western Washington peatlands and dated to be about 6,600 year b.p., is commonly found more than halfway up the stratigraphic sequence in the Puget Sound area (Foley, 2001).

Because peatland occurrence is determined primarily by the interactions of climate and topography (Zoltai 1988; Halsey et al. 1997), it is expected that relationships could be seen in the physiographic provinces with respect to landscape position, basin type, water flow and soil or peat type. Each of these topics will be discussed in turn. Appendix B contains a list of all *Sphagnum*-dominated peatlands identified for this report, arranged by county. Appendix B also contains data matrices on the various physical features of the *Sphagnum*-dominated peatlands that are presented here in summary form.

Landscape position.

Six categories are used to identify landscape positions of peatlands: floodplain, terrace, lacustrine, headwater, saddle and depressional. A **floodplain** position is considered to be associated with the areas surrounding a defined channel that contains at least seasonal surface waters which likely overflow from the channel and influence the peatland at least periodically. A **terrace** position is also located on a fluvial landform, but is at a higher elevation from the channel, generally on a floodplain that is no longer active. It could be a remnant from glaciofluvial times or stranded due to a river changing its course or drying up. **Lacustrine** positions are those associated with lakes. They could be adjacent to lakes, form in a band along the lake margin, or even occur as floating islands in a lake. A **headwater** position occurs at the head of a drainage basin where the water source is derived from the surrounding slopes. An outflow channel is sometimes present, which merges with other small channels to initialize a drainage course. A peatland occupies a **saddle** position when it occurs on a drainage divide, such that there is very little land area draining to the peatland, and water draining from it flows in different directions, to separate watersheds. Peatlands found in floodplain, terrace, lacustrine, headwater, and saddle landscape positions account for about half of the peatlands investigated. The other half of these peatlands are found in various slight depressions on lowland flats or as slight depressions in irregular plateaus and benches along hillsides. Peatlands in these landscape positions are considered **depressional** ecosystems.

In western Washington as a whole, *Sphagnum*-dominated peatlands are most commonly found in depressional postitions. Following this, lacustrine positions are most common. The same pattern is true in each of the provinces except the Willapa Hills where the majority of the peatlands occur in inter-dune depressions. Figure 2.8 shows the relative distribution of some landscape positions by physiographic region, excluding the Willapa Hills region. The totals do not add up to 100% because the depressional position, which is thought to represent the most common landscape position for peatlands, could not be verified with certainty from the resources at hand (topographic maps and air photos). In the Cascade Mountain physiographic province, headwater peatlands are nearly as abundant as lacustrine peatlands, followed closely by floodplain and then terrace positions. This differs from the Puget Sound physiographic province where the lacustrine positions are more than four times as abundant as headwater positions. Floodplain, terrace, and saddle positions are relatively uncommon, occurring in less than 10% of peatlands in the Puget Sound physiographic province. This difference can be explained by the differences in physiography of the regions. The Puget Sound physiographic province is characterized by an abundance of glacial lakes (Hansen 1947) that provide many potential lacustrine sites for peatland development. In the lower elevation areas of the Cascade Mountains, below 610 meters (about 2,000 feet), lake basins are less common and peatland development is concentrated in floodplain and terrace landscapes (i.e., those with shallow slopes), and in headwater regions where slow moving water accumulates in shallow depressions before forming first order streams.

The landscape positions of *Sphagnum*-dominated peatlands in the Olympic Mountain physiographic province more commonly reflect lacustrine than other landscape positions (except depressional). Peatlands, however, occur more frequently in the other landscape positions compared to the Puget Sound province. Lowlands in the Olympic Mountain province have both steep terrain, where peatlands develop in valleys or headwater areas, as well as large, flat regions of uplifted coastal plain, more similar to Puget Sound, where lakes are abundant.

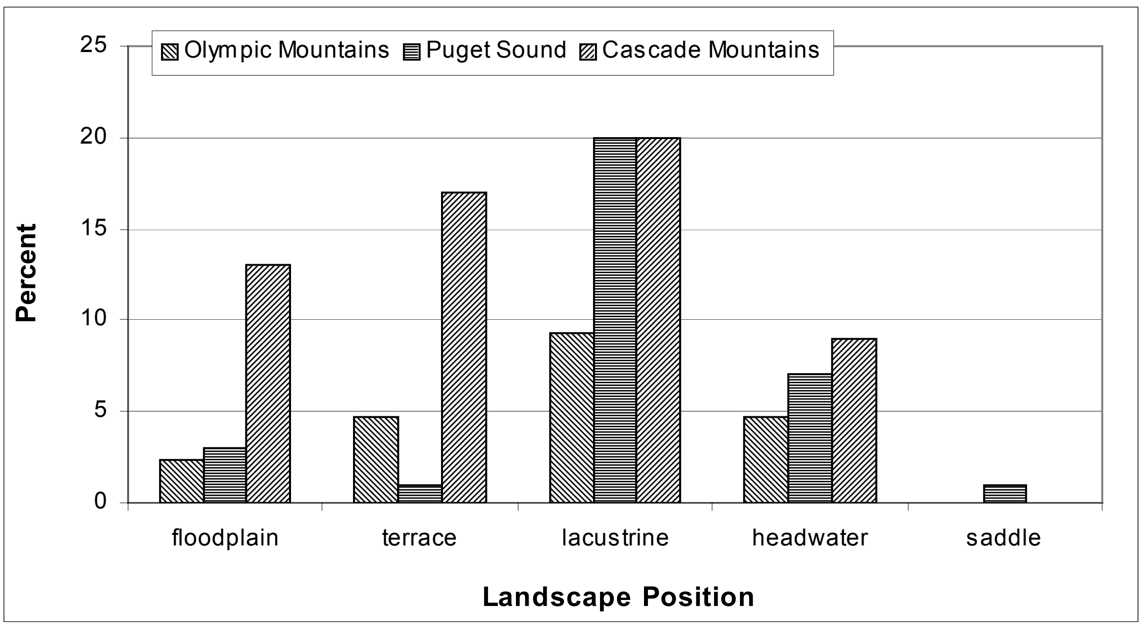

FIGURE 2.8 Distribution of peatland landscape postion for western Washington Physiographic Provinces (depressional position makes up the balance).

Basin Type

In addition to the landscape position, the types of basins in which the *Sphagnum*-dominated peatlands of western Washington have developed can be differentiated. Information on the type of basin is important in understanding the nature of individual peatlands and how they developed. For instance, glacial lake basins in the Puget Sound physiographic province are known to have four common origins: (1) kettle lakes, (2) morainal lakes, (3) lakes formed in drainage channels dammed by glaciofluvial deposits, and (4) floodplain depressions in valleys of glacial streams (Hansen 1947). A peatland developing in any one of these diverse basin types could be described as lacustrine if a lake was still present, while two peatlands developing in a similar basin type could be classified differently if one had completely filled the basin with organic deposits while the other still surrounded a small lake. Although described as lakes, these classes depict different ways basins have been formed and can be applied to basins that have been filled with peat rather than water. Unfortunately, there is limited information on basin type available for many of the *Sphagnum*-dominated peatlands in the database. No basin types are described for peatlands in the Olympic Mountain physiographic province and only for a very limited number of sites in the Cascade Mountain province.

Kettleholes (and kettle lakes) originated from blocks of glacial ice caught in the morainal till or outwash deposits as glaciers melted (Wetzel 1983). The melting of these ice blocks resulted in shallow, irregular depressions of various sizes depending on the original dimensions of the ice blocks (Wetzel 1983). In the Puget Sound province, there are numerous examples of *Sphagnum*-dominated peatlands developing in kettleholes. **Morainal lakes** occupy irregular depressions formed in glacial drift. Specifically, these lakes occupy irregularities in the ground moraine. They were formed by deposition under the glacier as it was moving, as well as from deposits within the ice mass as it melted (Bradshaw and Weaver 1993). As was seen in the section on landscape position, it is in these depressions that western Washington *Sphagnum*-dominated peatlands most commonly develop, particularly in the Puget Sound physiographic province. Some also occur in the lower elevation regions of the Cascade Mountain province. The depressions and peat deposits vary in size.

Although no *Sphagnum*-dominated peatlands are known to have formed in valleys blocked by glacial deposition, a few deposits have formed in instances where valleys were blocked by other means. The Milton No. 2 deposit in Pierce County (Rigg 1958) is an example of a small valley being dammed by sediments of the Puyallup River, and the Pilchuck Creek deposit in Skagit County has formed over a logjam.

Floodplain depressions in valleys of glacial streams are seldom documented as locations of *Sphagnum*-dominated peatlands in western Washington. In the sites compiled for this study, only the Mosquito Lake peat area in the Cascade Mountain physiographic province, is identified as developing in a river valley shaped by glacial streams, although many peatlands occupying a landscape terrace position probably owe their origins to glacial waters.

Glacial scour lakes may also develop in depressions formed from the erosive forces of glaciers moving over the landscape (Cole 1983). Only one example of a *Sphagnum*-dominated peatland forming in such a deposit is documented in western Washington, at Camp Wesley Harris in the Puget Sound province.

Sphagnum-dominated peatlands forming in basins developed by means other than glacial activity are poorly documented in western Washington. Although many peatlands are described as occurring on floodplains and terraces, the type of depression occupied within these landforms is not specified.

As mentioned in the section on landscape position, the majority of the *Sphagnum*-dominated peatlands in the Willapa Hills physiographic province are found in inter-dunal areas. This landscape is shaped by wind shifting sands with peatlands developing in the troughs between the sand dunes. For the most part, the peat deposits occupy areas between longitudinal ridges running parallel to the shoreline, thought to represent successive beach ridges (Hansen 1947). This dune environment is presumably much younger than most landscapes in western Washington, being repeatedly modified by the continually shifting sands (Hansen 1947). The peat areas are correspondingly shallow with a maximum depth of 4 meters (13.4 feet), in a region surficially dominated by *Sphagnum,* to less than 2 meters (6.7 feet), in much of the surrounding non-*Sphagnum* wetlands (Rigg 1958).

Water Flow

Water flow within a peatland may be the most important factor controlling its development, yet it is not simple to quantify, particularly based on a single observation of a site. From the descriptive information available, the *Sphagnum*-dominated peatlands in western Washington receive inflow through seasonal flooding, defined channels, storm drains, subterranean flow, undefined overland flow, and springs. Many of the *Sphagnum*-dominated peatlands have outflows, which can be described as either seasonal, or defined channels, including pipes and ditches. In some cases, *Sphagnum*-dominated peatlands in western Washington are influenced by neither inflow nor outflow channels, contributing to their hydrological isolation from geogenous waters.

Peat Type

Most of western Washington has been included in soil surveys conducted from 1947 to 1986. The organic soils, mapped as various series, can be summarized according to the vegetation from which they were formed and the degree of decomposition that vegetation displays in the soil profile. An important initial distinction is that between muck soils and peat soils. Both are organic soils, but they differ in their level of decomposition (Soil Survey Staff 1951). In a muck soil, the organic remains are decomposed to the point where identification of plant parts is impossible, whereas, in peat soils, plant parts can still be identified (Soil Survey Staff 1951). In general, muck soils have a higher mineral content than peat but this is not used as a differentiating character (Soil Survey Staff 1951). With this basic distinction in the degree of decomposition made, peat and muck types can be further subdivided based on the origin of plant material. The many soil series used in the soil surveys can, thus, be grouped into seven basic classes, comprised of:

1) *Sphagnum* peat,
2) grass and sedge peat,
3) grass and sedge muck,
4) woody (tree and shrub) peat,
5) peat and muck formed from salt tolerant plants,
6) sedimentary peat formed from the remains of microscopic plants and colloidal or sedimentary materials, and
7) mucky mineral soils which contain organic materials but are either too thin to be considered peatland soils or have a large degree of mineral materials mixed with the organics.

Table 2.4 relates the soil names from soil surveys into these seven categories. Figure 2.9 shows the distribution of peat types by physiographic province.

TABLE 2.4 Specific soil names in each of seven categories.

Sphagnum Peat	Sedge and Grass Peat	Woody Peat	Sedimentary Peat	Sedge and Grass Muck	Salt Influenced peat and muck	Mineral Soils
Orcas peat	Mukilteo peat	Rifle peat	Tanwax peat	Semiahmoo muck	Tacoma peat	Borosaprists
Greenwood peat	McMurray peat			Shalcar muck	Tacoma muck	Bellingham mucky silt loam
	Seastrand mucky peat			Seastrand Variant muck Fishtrap muck Pangborn muck Dupont muck Mukilteo muck Shalcar Variant muck Mukilteo Variant muck Carbondale muck Seattle muck		

In both Pierce and Thurston counties, two soil surveys were conducted 20 years apart. The soil surveys of Pierce County were conducted in 1955 and 1975, while those in Thurston County were conducted in 1958 and 1982. The differences between the older and newer surveys are interesting. In Pierce County, three areas were identified with Greenwood peat (a *Sphagnum* peat soil) as part of the wetland complex in 1955 (United States Department of Agriculture 1955). In 1975, however, these areas were not delineated separately from the surrounding wetlands and were identified as being muck or mineral soils (United States Department of Agriculture 1975). In Thurston County, a similar trend was displayed with 9 of the 11 *Sphagnum*-dominated wetland sites mapped in both surveys, at least partially, as a peat soil in 1958 and as a muck soil in 1982 (United States Department of Agriculture 1958, 1982). The reasons for these discrepancies are unclear and it is unknown whether these changes result from:

a) actual changes in the physical properties of the soil, as a result of drainage, or hydrological modification of the watershed leading to a decomposition of the peat,
b) improved aerial photography and field verification, improving the quality of the mapping,
c) more recent surveys being mapped at a lesser level of detail, or
d) the working definitions of the soil series changing over time.

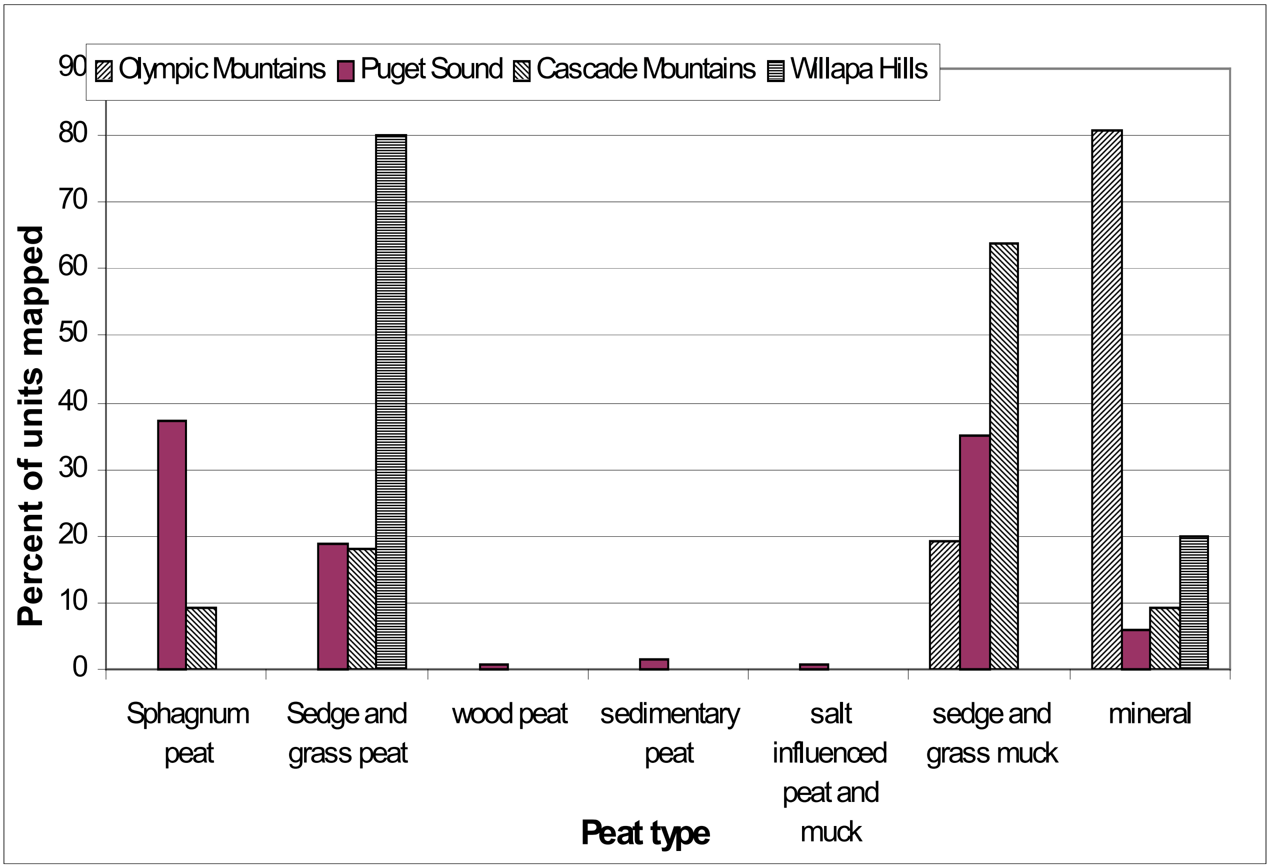

FIGURE 2.9 Distribution of peat types underlying *Sphagnum*-dominated peatlands by physiographic region (based on soil surveys)

It seems unlikely that the original soil surveys were inaccurate, and that the more recent descriptions represent a correction, since soil profiles by Rigg (1958) indicate that there was, in fact, Greenwood (*Sphagnum*) peat present at many sites, as mapped in the earlier surveys. This lends credence to the theory that the peat soils had indeed undergone further decomposition during the intervening 20-year time period, perhaps due to draining or other hydrological modifications associated with human activities in the area.

2.5 Watershed Characteristics of Western Washington Acid Peatlands

Watershed size

The area of surrounding land from which water flows towards an individual wetland is considered to be the watershed, or drainage area, for that wetland. Drainage areas of the *Sphagnum*-dominated peatlands in western Washington range in size from about 16 to 18,085 hectares (40 to 44,670 acres). Attempts to correlate wetland size with the extent of *Sphagnum* peat area or landscape position were unsuccessful. The inability to find relationships between these attributes is not really surprising. In flatter topographic areas, such as plateaus where *Sphagnum*-dominated peatlands typically develop, very large watersheds might result in only minimal transfer of runoff into peat areas, whereas in steeper areas, smaller watersheds might contribute proportionally more surface runoff to the *Sphagnum* community. In addition, incomplete data and knowledge of past disturbance history also make watershed size relationships difficult to identify.

Disturbance history

Various types of disturbance have been prevalent in the *Sphagnum*-dominated peatlands of western Washington this past century. Although natural forms of disturbance occur (e.g. fire, flooding and other hydrologic alterations) man-made disturbances are most likely to be reported. Some manner of man-made disturbance was reported in at least 45% of the *Sphagnum*-dominated peatlands and 42% of the associated watersheds comprising the sample for western Washington (see Table 2.5). Data supporting the summary information in the Table is given in Appendix C, "Supporting data and reports for Chapter 2."

TABLE 2.5 Percentage of *Sphagnum*-dominated peatlands in each physiographic province disturbed from their natural state.

Physiographic Province	% Total Sites Disturbed		
	Wetland	Watershed	N (number in sample)
Olympic Mountain	49	13	43
Puget Sound	49	46	176
Cascade Mountains	17	36	23
Willapa Hills	80	80	5
Western Washington	45	42	247

The degree of disturbance is also seen to varies by physiographic province, with the more remote Cascade Mountain province having a lower degree of peatland disturbance, and the large wetland complexes between sand dunes in the Willapa Hills province have a very high degree of disturbance. The type of disturbance is also of interest, and the two most common disturbance types within each province are given in Table 2.6, both for the peatland itself and for the surrounding watershed. From Tables 2.5 and 2.6, it is appears that the regions with the lowest disturbance percentages also had lower impact types of disturbance. Logging, grazing, and recreation are the most commonly identified disturbance types. These types of activities may have lower impacts on peatland processes and functions than direct disturbance of the peatland itself by mining, draining, logging, or farming.

In the Puget Sound and Willapa Hills physiographic provinces, the disturbance types were mining, logging, draining, and agriculture. The severe effect of mining and agriculture can be seen in two peatlands in the Puget Sound province. The Seola peat area and Cottage Lake peat area (Rigg 1958) provide two excellent examples of former *Sphagnum*-dominated peatlands in King County that have been subjected to the disturbances of mining and agriculture respectively, eliminating the areas of *Sphagnum* peat. The effect of logging in the watersheds of peatlands appears to be less severe than direct effects on the peatlands from mining, draining, and farming.

In the Puget Sound and Willapa Hills physiographic provinces, residential developments are beginning to encroach on *Sphagnum*-dominated peatlands (Table 2.6). The major population centers of western Washington, which occur in the Puget Sound province, coincide with the regions containing high numbers of *Sphagnum*-dominated peatlands. Due to this coincidence, the effects of urbanization may have a very significant negative influence on a large percentage of western Washington's *Sphagnum*-dominated peatlands. Potential impacts due to changes in water levels, nutrient and mineral enrichment, increased bacterial populations and direct physical effects of trampling and establishment of invasive species are also likely.

TABLE 2.6 Common disturbances of *Sphagnum*-dominated peatlands in western Washington.

Physiographic Province	Most Common Disturbance Types			
	Wetland		Watershed	
Olympic Mountain	logging	grazing	logging	-
Puget Sound	mining	logging	roads	residential
Cascade Mountains	logging	recreation	logging	roads
Willapa Hills	drainage	agriculture	logging	residential

2.6 Developmental Pathways and Isolating Mechanisms

Sphagnum-dominated peatlands in western Washington appear to have developed through two main processes. The first is the deposition of peat in lakes, termed terrestrialization. The second is the deposition of peat in marshes or swamps, called flow-through succession or topogenous development (Moore and Bellamy 1974 as cited by Mitsch and Gosselink 1993). Paludification, the spreading of *Sphagnum* sp. onto upland areas through the process of waterlogging, is not obvious in western Washington. A more detailed discussion of these successional processes is presented in the Succession section of Chapter 5. Both of the processes identified above can lead to peatlands dominated surficially by *Sphagnum*, but differing in terms of their underlying peat stratigraphy. The successional process by which peat accumulates in a lake basin, eventually leading to the establishment of a *Sphagnum*-dominated peatland, has not been studied in western Washington since the early 1900s (Rigg 1919, 1925, 1958; Rigg and Richardson 1933, 1938).

Sphagnum-dominated peatlands whose development is associated with lakes may be found in a number of situations. *Sphagnum* may be found encroaching on the margin of a lake, such as the Lake Twelve bog, King County #21, (Rigg and Richardson 1938) or completely surrounding a lake, such as the Sunnydale bog, King County #23 (Rigg and Richardson 1938). In other situations, the peatland has filled the entire basin leaving no visible lake, such as the Lake Forest Park bog (Rigg and Richardson 1938) which no longer exists. These peatlands all represent various stages in the lake-fill model of bog succession (Crum 1988) and indicate that this successional process occurs and has occurred in at least some of the peatlands of western Washington.

All three lake-fill sites mentioned above show four basic layers of peat accumulation in their peat profiles. At the base, all sites begin with a layer of lake mud over basal sands and clays (Rigg and Richardson 1938). This lake mud, later described by Rigg (1958) as sedimentary peat, is presumed to have settled in the lake and is composed of organic matter made up of microscopic remains of diatoms, algae, sponges and plants, mixed with mineral matter (Rigg and Richardson 1933). Various layers of fibrous peat lie above the sedimentary peat layer (Rigg 1958), including peats composed of sedges (*Carex* spp.), tules (*Scirpus* spp.) and reeds (*Phragmites* spp.) (Rigg and Richardson 1938). A partial, or sometimes complete, layer of woody peat is then formed over the fibrous peat, with the *Sphagnum* peat forming directly on either the fibrous peat or the woody peat (Rigg and Richardson 1938). At the margins of each of the profiles lies an area of muck containing organic material from decayed plants, as well as mineral soil from the adjacent slopes (Rigg and Richardson 1938). This depositional pattern is in agreement with the vegetational succession pattern proposed by Fitzgerald (1966) for the peatland surrounding King's Lake bog (King County #5). King's Lake bog is surrounded by a floating rush-*Carex* zone from which pioneering shrubs extend out into the lake. Bordering the rush-*Carex* zone, towards the shore, is another floating zone, dominated by *Sphagnum* and *Carex*, that is surrounded by a bog-shrub-tree zone, having a ground layer of *Sphagnum* (Fitzgerald 1966). Beyond that, the peatland is surrounded by a transition zone and marginal ditch zone, both of which are formed on a substrate of muck (Fitzgerald 1966).

Combining the peat stratigraphy with the surface vegetation patterns, a typical developmental history can be constructed. Initially, the sedimentary peat is deposited in the lake basin through settlement of material washed in from the surrounding slopes, as well as from microscopic organisms inhabiting the lake (Rigg 1958). While this sedimentary deposit is being formed, sedges and pioneer shrubs, growing at the lake margin begin to form a mat extending inwards towards the center of the lake. A thin, unstable mat of vegetation forms, which is fragile and pieces may break off, sinking to form the beginnings of a layer of fibrous peat on the lake bottom. As the mat gradually thickens, it enlarges and encroaches further on the lake (Fitzgerald 1966). This thickened region of the mat serves to isolate plants growing on it from the lake water, both horizontally and vertically (Vitt and Slack 1975). This allows *Sphagnum* species to become dominant, building further layers of peat. As the layers of peat build up above the level of the lake, precipitation becomes more important as a water and mineral source, and the lake water becomes less influential. In some instances, this developmental process favors the growth of *Sphagnum* and other plants adapted to acidic or mineral-poor environments (Crum 1988). In comparing the flora developing on alkaline and acidophilous bog lakes in northern Michigan, Vitt and Slack (1975) determined that distance from the water's edge served to isolate the vegetation from the influences of the lake water enough that in both instances, a common, relatively acidic, plant community developed.

Sphagnum-dominated peatlands may also be found away from lacustrine influences, isolated within marshes or swamps, such as in the Grayland peat area (Rigg 1958) or occupying a depression associated with neither a lake nor a larger wetland complex such as the Sooes River peat area (Rigg 1958). In such cases, *Carex* peat forms the basal deposit over mineral soil, lacking an intermediate layer of sedimentary peat (Rigg and Richardson 1933). The *Sphagnum* peat may then overlie *Carex* peat, completely dominating the peat area, as is the case in the Sooes River peat area (Rigg 1958), or only occur in patches, with much of the peatland surface still being dominated by marsh or fen vegetation, as in the Grayland peat area (Rigg 1958). The colonization of *Sphagnum* in these fen or marsh areas occurs when the build-up of peat has caused the bases of the sedges or shrubs to rise above the influence of the mineral-rich surface water, causing rainfall to have a greater influence on water chemistry (Hebda et al. 2000). As with lake-infill succession, this favors the growth of *Sphagnum* mosses. Glaser (1983) mentions the development of *Sphagnum* islands in stagnation zones where geogenous runoff is minimal. Thus obstructions to flow could also act as an isolating mechanism to encourage the development of peat profiles.

On the eastern coast of North America, Damman (1986) describes a zone of topogenous peatlands near the southern distribution limit of *Sphagnum*-dominated peatlands, with raised, ombrogenous bogs occurring only farther north, where there is adequate precipitation. Extending only to the south coast of Oregon (Halsey et al. 2000), *Sphagnum*-dominated peatlands of western Washington are also near the limits of their geographical range. If trends similar to those observed by Damman (1986) also occur on the West Coast, many of the peatlands, particularly those in areas of lower precipitation, may be climatically limited from forming a true ombrogenous system. However, the precipitation and evaporation data examined previously clearly show a positive water balance, at least for the Puget Sound physiographic province. In some continental regions, reversals in groundwater flow creating a discharge environment under the peat mound, have been found to counteract the climatic moisture limitations and allow the formation of ombrogenous peatlands even where the water balance is marginal (Glaser et al. 1997). No such hydrological studies have been conducted in western Washington, so it is unknown if groundwater reversals play an important part in the development of *Sphagnum*-dominated peatlands in western Washington.

2.7 Chapter Two References

Bradshaw, M. and R. Weaver. 1993. Physical Geography An Introduction to Earth Environments. Mosby-Year Book, Inc. Toronto.

Cole, G.A. 1983. Textbook of Limnology. 3rd edition. C.V. Mosby Company, Toronto.

Crum, H.A. 1988. A Focus on Peatlands and Peat Mosses. Ann Arbor, The University of Michigan Press.

Damman, A.W.H. 1986. Hydrology, development, and biogeochemistry of ombrogenous peat bogs with special reference to nutrient relocation in a western Newfoundland bog. Canadian Journal of Botany 64(2):384-394.

DuRietz, G.E. 1949. Huvidenheteroch huvidgrünser I Svensk myrvegetation. Summary: Main units and main limits in Swedish mire vegetation. Svensk Botanisk Tidskrift 43(2-3): 274-309.

Easterbrook, D.J. and D.A. Rahm. 1970. Landforms of Washington the Geologic Environment. Union Printing Co., Bellingham, Washington.

Engstrom, D.R. 1984. Lake development in the boreal peatlands of southeastern Labrador, Canada. Arctic and Alpine Research 16:4467-452 (as cited by Winkler 1988).

Fenneman, N.M. 1931. Physiography of Western United States. McGraw-Hill, New York.

Fitzgerald, B.J. 1966. The microenvironment in a Pacific Northwest bog and its implications for establishment of conifer seedlings. MSc. Thesis. University of Washington.

Franklin, J.F. and C.T. Dyrness. 1973. Natural Vegetation of Oregon and Washington. USDA Forest Service General Technical Report PNW-8. US Department of Agriculture, Portland, Oregon.

Glaser, P.H. 1983. Vegetation patterns in the north Black River peatland, northern Minnesota. Can J. Bot 61: 2085-2102.

Glaser, P.H., D.I. Siegel, E.A. Romanowicz, and Yi Ping Shen. 1997. Regional linkages between raised bogs and the climate, groundwater, and landscape of north-western Minnesota. Journal of Ecology 86: 3-16.

Gore, A.J.P. 1983. Introduction. *In* Ecosystems of the World. Volume 4A. Mires: Swamp, bog, fen and moor. A.J.P. Gore. editor. Elsevier Scientific Publishing Company, Amsterdam, Netherlands. pp. 1-34.

Halsey, L.A., D.H. Vitt, and L.D. Gignac. 2000. *Sphagnum*-dominated peatlands in North America since the last glacial maximum: their occurrence and extent. The Bryologist (in press June 2000).

Halsey, L., D. Vitt, and S. Zoltai. 1997. Climatic and physiographic controls on wetland type and distribution in Manitoba, Canada. Wetlands 17(2): 243-262.

Heinselman, M.L. 1970. Landscape Evolution, Peatland Types, and the Environment in the Lake Agassiz Peatlands Natural Area, Minnesota. Ecol. Monographs 40:235-261.

Hansen, H.P. 1947. Postglacial forest succession, climate, and chronology in the Pacific Northwest. Transactions of the American Philosophical Society, new series volume 37, part 1.

Hebda, R.J., K. Gustavson, K. Golinski, and A.M. Calder. 2000. Burns Bog Ecosystem Review Synthesis Report for Burns Bog, Fraser Delta, South-western British Columbia, Canada. Environmental Assessment Office, Victoria, B.C.

Kruckeberg, A.R. 1991. The Natural History of Puget Sound Country. University of Washington Press, Seattle, Washington.

Malmer, N. 1985. Remarks to the classification of mires and mire vegetation-Scandinavian arguments. Aquilo ser. Botanica 21: 9-17.

Malmer, N. 1986. Vegetational gradients in relation to environmental condition in northwestern European mires. Can. J. Bot. 64: 375-383.

Malmer, N., D.C. Horton, and D.H. Vitt. 1992. Element concentrations in mosses and surface waters of western Canadian mires relative to precipitation chemistry and hydrology. Ecography 15(1): 114-128.

McNamara, J.P., D.I. Siegel, P.H. Glaser, and R.M. Beck. 1992. Hydrogeologic controls on peatland development in the Malloryville Wetland, New York (USA). Journal of Hydrology 140(1-4):279-296.

Mitsch, W.J., and J.G. Gosselink. 1993. Wetlands. 2nd Edition. Van Nostrand Reinhold, New York.

Moore, P.D. and D.J. Bellamy. 1974. Peatlands. Springer-Verlag, New York.

Personal Communication, Steve Foley, Senior Engineer, King County Water and Land Resource Division. January, 2001.

Podniesinski, G.S. and D.J. Leopold. 1998. Plant community development and peat stratigraphy in forested fens in response to ground-water flow systems. Wetlands 18(3): 409-430.

Rigg, G.B. 1916. A summary of bog theories. The Plant World 19(10): 310-325.

Rigg, G.B. 1919. Early Stages in Bog Succession. Pub. Puget Sound Biol. Station. 2: 195-210.

Rigg, G.B. 1925. Some *Sphagnum* bogs of the north Pacific Coast of America. Ecology. 6(3): 260-279.

Rigg, G.B. 1940. The development of *Sphagnum* bogs in North America. Botanical Review 6: 666-693.

Rigg, G.B. 1958. Peat Resources of Washington. Division of Mines and Geology, Bulletin No. 44, State of Washington.

Rigg, G.B. and C.T. Richardson. 1934. The development of *Sphagnum* bogs in the San Juan Islands. American Journal of Botany. 21(10): 610-622.

Rigg, G.B. and C.T. Richardson. 1938. Profiles of some *Sphagnum* bogs on the Pacific Coast of North America. Ecology. 19(3): 408-434.

Siegel, D.I. and P.H. Glaser. 1987. Groundwater flow in a bog-fen complex, Lost River Peatland, Northern Minnesota. Journal of Ecology 75: 743-754.

Sjörs, H. 1950. Regional studies in North Swedish mire vegetation. Botaniska Notiser: 173-222.

Soil Survey Staff. 1951. Soil Survey Manual. U.S. Department of Agriculture Handbook No. 18. United States Department of Agriculture, Washington D.C.

United States Department of Agriculture. 1955. Soil Survey Pierce County Washington. Series 1939, No.27.United States Department of Agriculture, Soil Conservation Service in cooperation with the Washington Agricultural Experiment Station and the Washington State Planning Council.

United States Department of Agriculture. 1958. Soil Survey Thurston County Washington. Series 1947, No.6. United States Department of Agriculture, Soil Conservation Service in cooperation with Washington Agricultural Experiment Station.

United States Department of Agriculture. 1975. Soil Survey of Snoqualmie Pass Area, Parts of King and Pierce Counties, Washington. United States Department of Agriculture, Soil Conservation Service in cooperation with Washington State Department of Natural Resources, U.S. Department of Agriculture, Forest Service; and Washington State University, Agriculture Research Center.

United States Department of Agriculture. 1982. Soil Survey of Thurston County, Washington. United States Department of Agriculture, Soil Conservation Service in cooperation with Washington State Department of Natural Resources and Washington State University, Agriculture Research Center.

Vitt, D.H. 1994. An overview of factors that influence the development of Canadian peatlands. Memoirs of the Entomological Society of Canada 169: 7-20.

Vitt, D.H. and N.G. Slack. 1975. An analysis of the vegetation of *Sphagnum*-dominated kettle-hole bogs in relation to environmental gradients. Canadian Journal of Botany 53(4): 332-359.

Wetzel, R.G. 1983. Limnology. 2nd edition. Saunders College Publishing, Harcourt Brace Jovonovich Inc. Orlando, Florida.

Weider, R., M. Novak, W. Schell and T. Rhodes, 1994. Rates of peat accumulation over the past 200 years in five Sphagnum-dominated peatlands in the Unitied States. J. of Paleolimnology 12: 35-47.

Winkler, M.G. 1988. Effect of climate on development of two *Sphagnum* bogs in south-central Wisconsin. Ecology 69(4):1032-1043.

Zoltai, S.C. 1988. Wetland Environments and Classification. In: Wetlands of Canada. National Wetlands Working Group Canada, Committee on Ecological Land Classification. Ecological Land Classification Series No. 24. Polyscience Publications Inc., Montreal, Quebec.