

Perched Ponds: An Arctic Variety

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ABSTRACT. Data obtained during several seasons of field research on a small drainage basin in the Colville River delta of northern Alaska were used in a study of permafrost as an aquaclude for the maintenance of a pond above the regional water table. The development of the active layer of permafrost in the basin and the water budget of the pond were monitored. It was shown that the permafrost table enables the general form of the basin's subaerial surface to be maintained throughout the thaw season. The resulting prevention of percolation, when combined with a low evaporation rate, is sufficient to ensure that the pond is perennial.

RÉSUMÉ. *Étangs surélevés: une variété arctique.* Des données obtenues au cours de plusieurs saisons de recherches sur les lieux d'un petit bassin de drainage dans le delta de la rivière Colville dans l'Alaska du Nord furent utilisées pour maintenir un étang au-dessus du niveau hydrostatique régional en se servant du pergélisol pour enfermer l'eau. Le développement de la couche active du pergélisol dans le bassin et la quantité d'eau de l'étang furent contrôlés et enregistrés. Il fut démontré que le niveau du pergélisol permet à la forme générale de la surface subaérienne du bassin de rester stable pendant toute la saison du dégel. L'absence d'infiltration qui en résulte, lorsqu'elle est combinée avec un taux bas d'évaporation, est suffisante pour assurer la perpétuité de l'étang.

РЕЗЮМЕ. *Арктический тип водоемов с подвешенным водным зеркалом.* Данные, собранные за несколько сезонов полевых работ по обследованию небольшого водосборного бассейна в дельте р. Колвилл на северной Аляске, использовались для изучения многолетней мерзлоты как водоупора, поддерживающего уровень воды в водоеме выше регионального горизонта грунтовых вод. Ведся контроль за образованием активного слоя многолетней мерзлоты и водным балансом водоема. Было показано, что горизонт многолетней мерзлоты позволяет сохранять общую форму субареальной поверхности бассейна во время оттепели. Отсутствие просачивания в сочетании с низкой скоростью испарения оказывается достаточным для того, чтобы водоем был постоянным.

INTRODUCTION

The Coastal Plain of northern Alaska is characterized by continuous permafrost, a thin active layer, a short snow-free period, cool summers, low evaporation rates, and tundra vegetation. Further, it possesses low-gradient slopes which, in combination with the above conditions, cause poor drainage and account for the numerous lakes and ponds characteristic of the region (Walker 1974). Lakes vary greatly in number and size across the Coastal Plain; in some regions they occupy as much as 90% of the surface area (Brewer 1958).

Thaw lakes, especially the oriented variety, have been studied by a number of researchers (Hopkins 1949; Carson and Hussey 1959; Hussey and Michelson 1966; Sellman *et al.* 1975). However, the other types of lakes in the Alaskan Arctic have been virtually ignored. In the glaciated portions of the Brooks Range

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and Foothills glacial lakes are numerous (Hobbie 1974); along most rivers and in most deltas typical floodplain lakes are common (Walker 1974); and the centres of, and troughs between, ice-wedge polygons are frequently occupied by water.

A type of Arctic pond that has received little attention to date is one that exists in the sand dunes of the North Slope (Walker 1967). It might be considered an Arctic member of the family of perched lakes, which are common in many parts of the world.

Perched lakes

Veatch and Humphreys (1964 p. 164) defined a perched lake as "... a perennial lake which has a surface level lying at a considerably higher elevation than that of other waterbodies directly adjacent or closely associated." In order for perched lakes to exist, an aquaclude must be present between the water table associated with the lake and the regional water table. Such aquacludes have been described many times and include glacial till (Veutch *et al.* 1906), impervious clays (Stearns *et al.* 1939), humus-bound sand ("coffee rock") and aeolianite (Jennings 1957), organic cemented sand (Coaldrake 1960), glacial ice (Ricker 1962), playa clays (Motts 1965), and humate (Swanson and Palacas 1965), to mention but a few. Permafrost, the aquaclude discussed in this paper, contrasts with the other types just referred to, with the possible exception of glacial ice, in that its presence depends upon the temperature regime of the lake site rather than depositional history.

PERMAFROST, THE ACTIVE LAYER, AND ARCTIC LAKES

Permafrost, defined as any material in which the temperature has remained continuously below 0°C for two or more years (Muller 1947), "... acts as an impermeable barrier to the movement of ground water, because the pore spaces are generally filled with ice within the zone of saturation" (Williams 1970 p. 2). Recharge, discharge, and movement of ground water are restricted, and therefore permafrost provides the potential for perching. Nonetheless, to date, the aquaclude nature of permafrost has not been singled out as a perching mechanism.

All of the North Slope is in the zone of continuous permafrost, *i.e.*, in the zone where climatic conditions are such that regionally the ground temperature remains continuously below 0°C. The only surface areas within this region not underlain by permafrost are those where deep bodies of water are present (for example, beneath deep river channels and deep lakes). In these locations there is a thaw bulb which may extend through the permafrost to the non-frozen layers beneath (Lachenbruch *et al.* 1962). The size and thickness of these non-permafrost zones depend on the dimensions of the water bodies and their age. On the average, water on the North Slope freezes to depths of two metres during winter. Water bodies deeper than 2-3 metres do not freeze to the bottom.

The active layer is an integral part of permafrost environments and is the layer which seasonally thaws and freezes. Its base is a permafrost table that may vary in depth slightly from year to year in response to climatic conditions. In any event, in the zone of continuous permafrost the concept of a regional water table has

little significance, for ground-water flow is limited to movement in the active layer (usually never more than two metres thick on the North Slope) during the few months of summer. Thus, most lakes, regardless of size, have essentially their own water table.

Permafrost effectively isolates nearly all lakes on the North Slope. The duration and abundance of lakes can be attributed mainly to the inhibited drainage caused by permafrost and to the relatively low levels of evaporation. Thaw lakes (the type of Arctic lake that has received the greatest attention to date) develop as a result of the subsidence that follows thawing of the permafrost (Hopkins 1949). In contrast, perched lakes, as discussed in this paper, develop when permafrost forms in a basin.

SAND DUNES AND PERCHED LAKES

Most lakes in the tundra do not have a surface level lying at a considerably higher elevation than adjacent waterbodies, as required by the definition of perched lakes quoted above. For such a condition to exist, a highly irregular local relief is necessary — a relief such as is found in moraine or dune topography. Moraine topography is confined to the Foothills section north of the Brooks Range and is not present on the Coastal Plain. However, the Coastal Plain does contain numerous sand dune areas in which local relief may reach ten metres (Black 1951; Walker 1967).

Sand dunes are best developed along rivers or in association with large lakes. The prevailing winds on the Coastal Plain are from the northeast, so that dune areas tend to be found on the southwestern sides of river channels and lakes. The size of the dunes is mainly determined by the size of the sand bars upwind of the dune area.

Some of the best developed dunes to be found in northern Alaska are in the Colville River delta, where they line much of the left bank of most of the delta's distributaries (Fig. 1) (Ritchie and Walker 1974). Stabilized and active dunes are both present, but the active dunes possess the greater amount of local relief. Stabilized dunes are covered with vegetation, have generally smooth, rounded shapes, and have few depressions in which water can accumulate. In contrast, active dunes possess a highly irregular relief and provide two types of closed basin: one, the interdune basin, which develops as a dune field moves inland from a river bar, is elongated parallel to the sand field, while the other develops within a dune field where blowouts are common. These blowout basins are usually elongated parallel to windflow, i.e., nearly perpendicular to the orientation of the dune field (Fig. 2), and are referred to as intradune basins (Walker 1967).

Delta dunes consist mainly of fine or very fine sand, although coarse sand and even fine gravel occur in the bowls of some of the blowouts. Organic matter is minimal, although willow roots and the roots of a variety of grasses help bind the sand in place.

In the Colville Delta nearly every dune system has both types of basin, and many of these contain ponds. Within 50 metres of Camp Putu (one of the field stations operated by the Naval Arctic Research Laboratory, Barrow, Alaska),

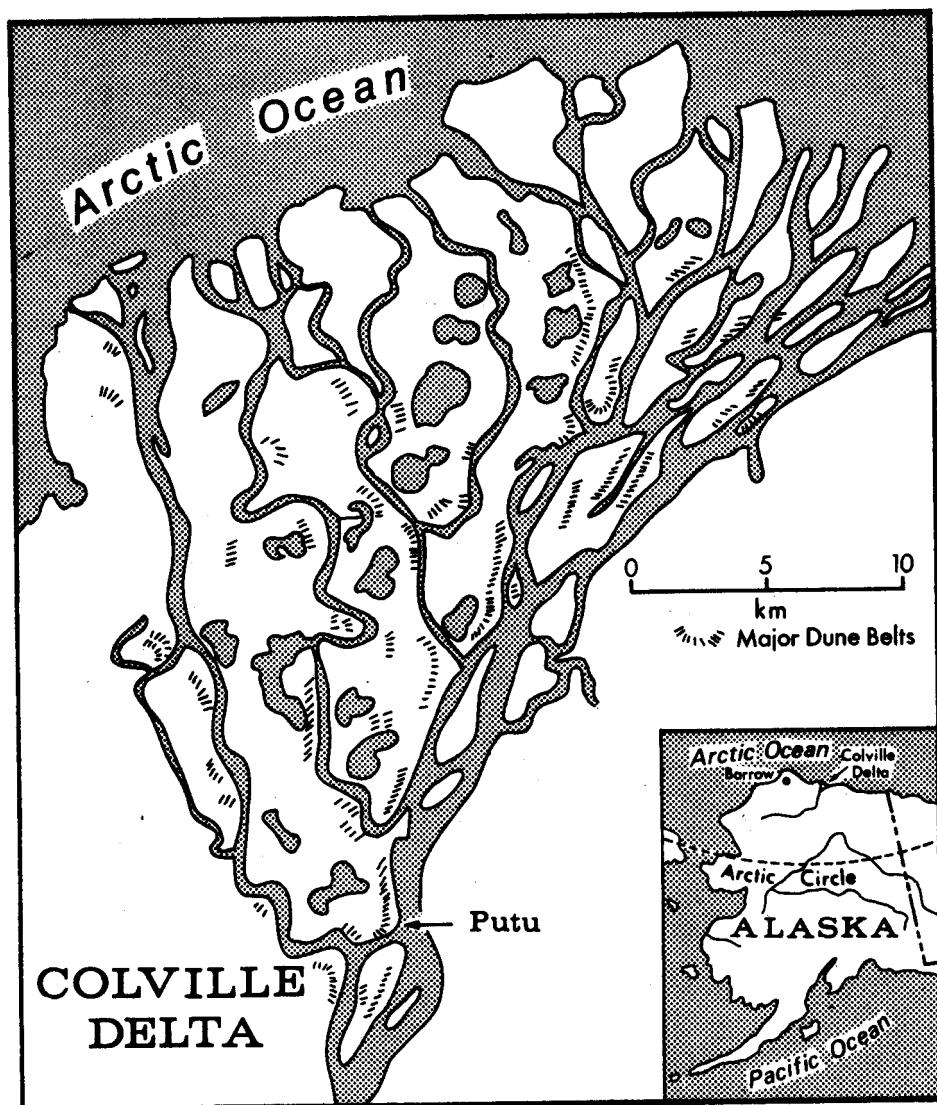


FIG. 1. Colville River delta: location and distribution of sand dunes.

at the head of the Colville River delta, are three intradune ponds (Figs. 1 and 2). The southernmost pond, herein named Putu Pond, was selected for detailed study.

PUTU POND AND ITS DRAINAGE BASIN

Putu Pond, an elongated ellipse, occupies the centre of an irregularly shaped dune basin (Figs. 2 and 3). The basin, 96 m long and 31 m wide across its widest section, is 2,060 m² in area. The pond varies in surface area from 310 m² at overflow stage to about 100 m² at the time freezeup begins.

The crest of its basin varies between 10.2 m and 13.7 m above sea level,

FIG. 2. Camp Putu and intradune ponds. The overflow drainage channel is indicated by "a".

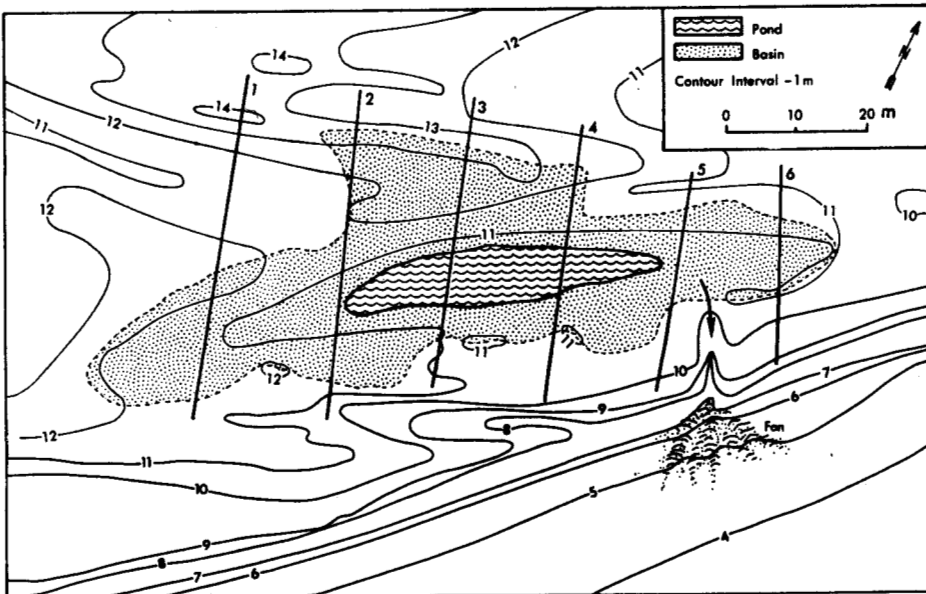
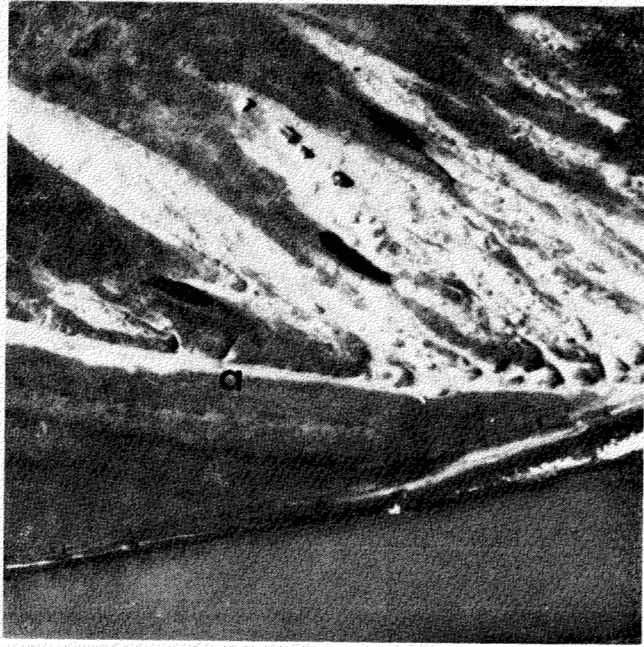


FIG. 3. Map of Putu Pond and basin.

the lowest edge being about 6 m above the mudflat at the base of the dunes, 15 m away. The lowest part of the basin is 9.2 m above sea level, and maximum relief is more than 4 m. Pond depth varies during the summer between about 0.6 m and 1.3 m at the pond's deepest spot.

The surface of the basin slopes, with various degrees of steepness, toward the

pond. Its surface is covered with a highly varied vegetation ranging from thick mats of moss, through grasses and flowering plants, to willows which, especially at the western end of the pond, are as much as 2 m tall (Fig. 4). Part of the surface is non-vegetated, although such areas often contain roots from adjacent plants. In this dune belt, willow roots occasionally extend horizontally more than 10 m just beneath the surface. The dune area is colonized by ground squirrels, which play a very important role in dune modification. Occasional caribou herds move across the surface, and birds frequently nest within the basin.

Virtually all characteristics of the pond and its basin are affected by the extreme seasonality that is typical of the Arctic. There are four periods of highly varied duration. During most of the year the basin is covered with a layer of snow and the pond and active layer are frozen. This period, winter, lasts between seven and eight months. Spring, the season of melting snow and ice within the basin, is short, lasting less than a month. Summer, which is characterized mainly by a gradual lowering of pond level and a gradually decreasing rate of active-layer development, extends from about mid-June to mid-September. Fall, like spring, is short and is the period during which the pond freezes and the snow cover begins to form.

From the standpoint of perching, the two most distinctive changes that occur within the basin are the development of the active layer and the seasonal water-budget cycle. Although in nature these two phenomena are not mutually exclusive, in this report they are separated for clarity of presentation.

DEVELOPMENT OF THE ACTIVE LAYER

Restricted thawing of the active layer in the basin ensures maintenance of the pond throughout the summer season. In order to monitor active-layer development,

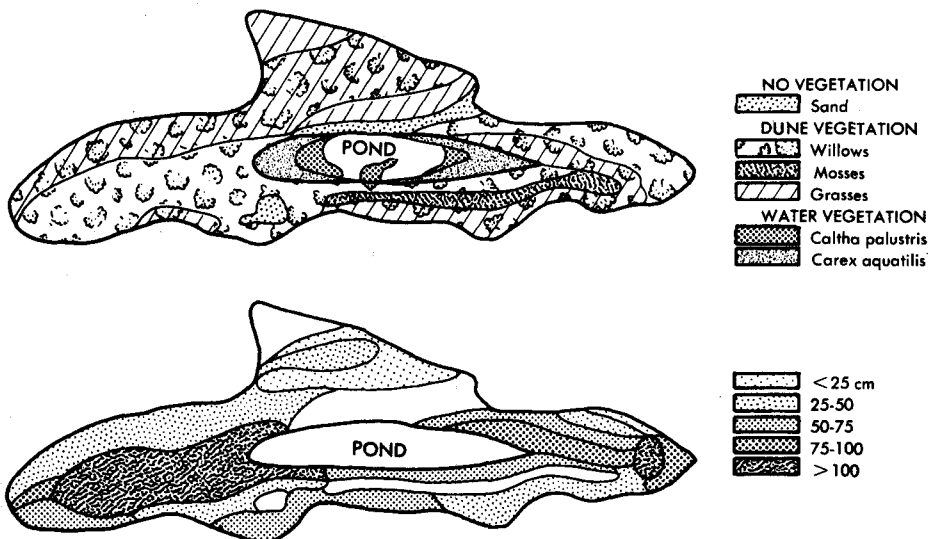


FIG. 4. Biotic maps, Putu Pond and basin.

depth measurements were made with a two-metre-long probe once a week at intervals of 1.5 m along six sections (Fig. 3) across the basin and three additional shorter sections across the pond.

Initiation of thaw appears to occur within a few hours of the final removal of snow from the surface. From the monitoring of test plots on sand dunes during the snowmelt period it was shown that as long as snow is present, even though air temperatures may be quite high, the sand will thaw no more than a few centimetres (Fig. 5). In the drainage basin of Putu Pond, the snow first disappears from the south-facing, steep slopes of non-vegetated sand. Removal occurred in some areas in early May; the last snow did not melt from beneath some willows near the head of the pond until over a month later. Thus, initiation of active-layer thaw ranges over a month in the basin.

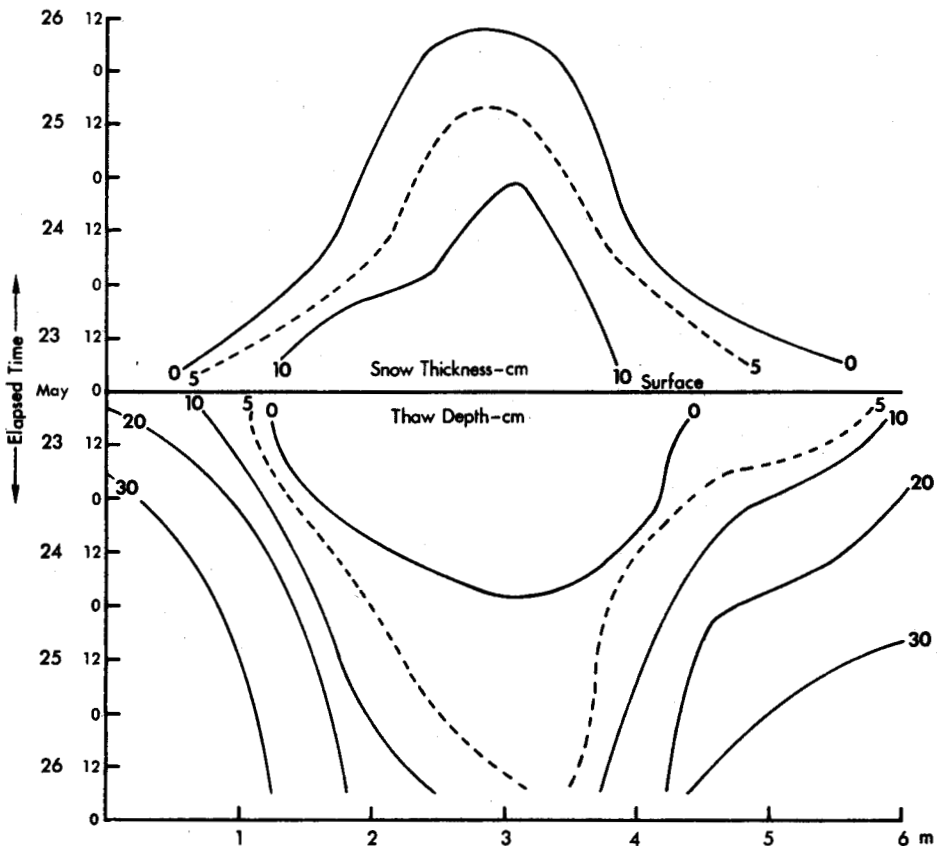


FIG. 5. Snowmelt and dune thaw with time (in hours) along a 6-metre section on a flat, bare surface, 23-26 May 1971.

In Fig. 6, the development of the active layer is illustrated for the third of the six sections for 1962. All six sections displayed a similar trend for the other years in which data were collected (1964, 1966, 1971, and 1973). Along the third section in 1962, there was great variation in the date when the active layer reached

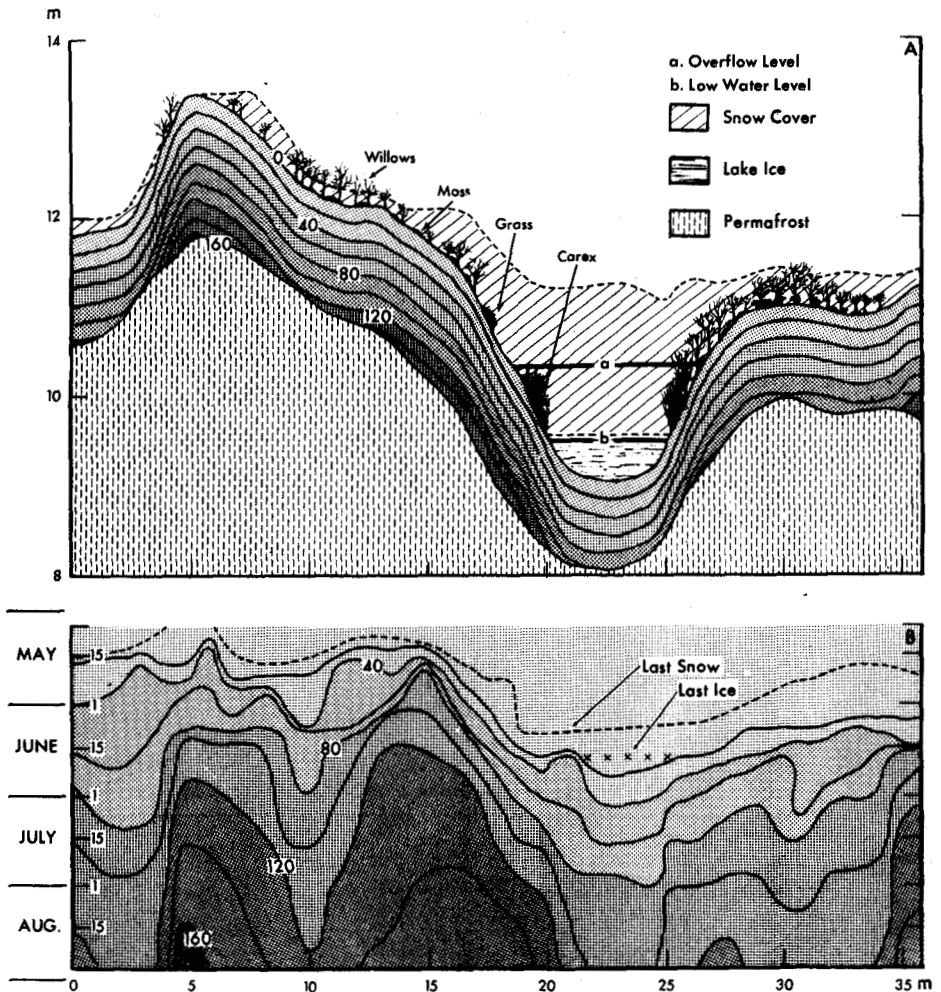


FIG. 6. The active layer in Putu basin: A. Vertical development (metres above mean sea level); B. Temporal development (active layer depths in centimetres, horizontal distances in metres).

specific depths. For example, the date when the active layer had thawed to a depth of 20 cm ranged from 12 May under exposed sand surface to 13 June beneath the lake. The mean comparable date beneath moss- and willow-covered surfaces was 5 June. An active-layer thickness of one metre was reached on the southward-facing portion of the section under sand by mid-June, whereas such thickness never occurred beneath the pond.

In order to determine the relative rates of development, as between different areas within the basin, active-layer thaw values for all probes were divided into groups on the basis of surface cover (exposed sand, willow, moss, or water). It was found that beneath all types of cover the seasonal variation of thaw is similar in that, once thaw is initiated, it progresses rapidly until about the end

of July. In 1962, rates during this period ranged from 1.6 cm per day beneath exposed sand, through 1.5 cm per day beneath the pond and 1.2 cm per day beneath moss, to a low of 1.1 cm per day beneath willows. After July there was a generally decreasing rate of thaw beneath all surfaces.

The 1973 data for willows were divided into two groups, related respectively to low and high willow areas. It was found that low willow areas have a greater variability of active-layer development than high willow areas. High willows are located in the sheltered bottom of the basin, where there is little variation in active layer. In contrast, low willows are found in much more diverse situations.

The rates of development for 1962 and 1973 are represented graphically in Fig. 7.

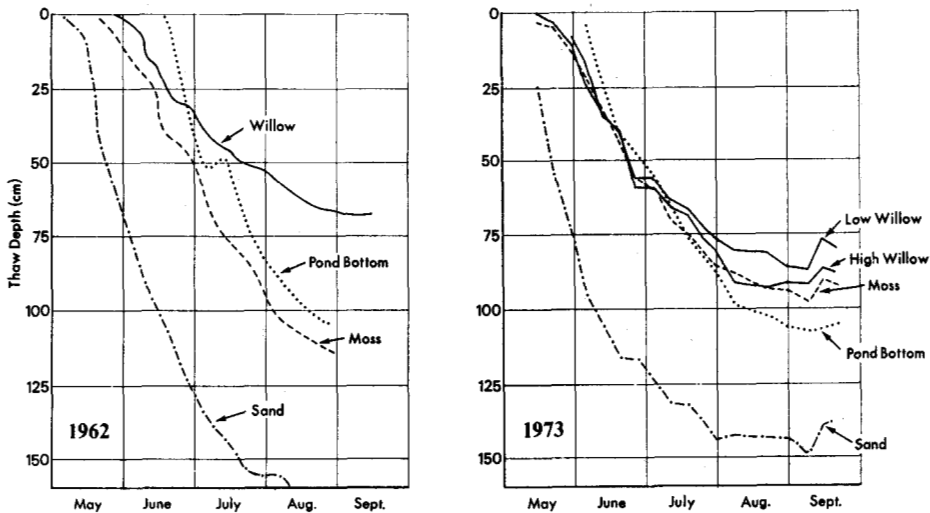


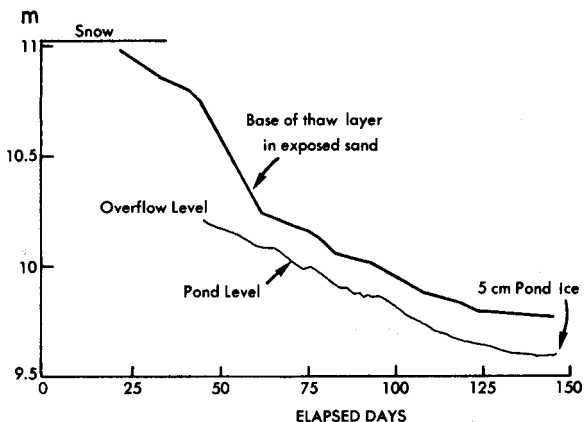
FIG. 7. Thaw development curves, 1962 and 1973.

The environments within the basin where development of the active layer is most regular are those where high willows, sand, and water are present. The greatest variability occurs beneath low willow and moss covers. The areas of sand and water are characterized by a greater evenness of heat distribution than the vegetated areas, which, even when covered primarily with the same species of plants, vary significantly in size, orientation, exposure, and spacing.

Although the rate of thaw beneath the pond is nearly as rapid as that beneath exposed sand, the long delay in time before thaw begins limits the total thaw to only about 60% of that beneath exposed sand.

At the end of the thaw season the permafrost table provides a profile that is similar to the profile of the surface (Fig. 6A). Although by this time permafrost-table relief is about one metre less than that of the surface, the variation is insufficient to eliminate permafrost as an aquaclude within the basin, since the level of the permafrost table around the pond exceeds that of the pond water itself (Fig. 8).

FIG. 8. Relation between thaw depth in sand surrounding Putu Pond and water level (metres above mean sea level).



PUTU POND WATER BUDGET

Whereas the presence of a permafrost table which parallels the surface contours of the dunes is responsible for providing the aquaclude needed for perching, it is the nature of the water budget in the basin that ensures adequate water for maintenance of the pond. The several factors involved include snow accumulation during winter, sublimation of snow, runoff from the basin, temperature and evaporation, precipitation during summer, and lateral movement of water through the sand above the aquaclude.

Snow and ice

Measurements of depth and density of snow were taken during several seasons in Putu basin. The irregular surface of the basin results in an uneven distribution of snow (Fig. 6A). Even in midwinter, the snow is shallow along the crest, some portions of which are occasionally clear of it. Drifts accumulate to thicknesses of 1.75 m in the basin where, by midwinter, the amount of snow reaches nearly equilibrium conditions, with densities averaging 30-40%. The variability of snow density with depth, which is low in winter, increases as the melt season proceeds (Table 1).

In 1971, the quantity of snow remained basically the same until mid-May, when melting, evaporation, and sublimation began to increase in intensity (Table 2). During thaw, meltwater percolated down through the snow; much of it refroze in the bottom layers, and an increase in density resulted (Table 2). In 1962, prior to snowmelt, the basin contained 1,240 m³ of snow at an average density of 37% for a water equivalent of 459 m³.

The quantity of ice in the pond varies from year to year, depending upon water depth at the time of freezeup. In 1971, the volume of ice was 21 m³. Melting of pond ice is delayed because it is protected by the snow cover for many days (Fig. 6B).

Overflow

Although much of the initial meltwater percolates into the snow and refreezes,

TABLE 1. Snow density and depth over pond centre

24 May 1971		13 May 1973	
Depth (cm)	Density (%)	Depth (cm)	Density (%)
5	42	5	40
20	39	20	42
35	34	35	36
50	45	50	39
65	49*	65	36
		80	33
		95	39

*Refrozen melted snow

TABLE 2. Snow characteristics, 1971

	Volume (m ³)	Average density (%)	Water equivalent (m ³)
25 April	948	33	312
15 May	896	36	323
23 May	457	46	210

it eventually begins to accumulate at the bottom of the pack. In the case of Putu Pond, meltwater gradually increases in depth at the base of the snow, especially on the surface of the ice. As the snow melts, the layer of water eventually reaches a level at which overflow occurs. The date on which overflow is initiated, and the duration of overflow, vary with the quantity of snow in the basin and with the nature of the temperature-and-precipitation regime during the melt season (Table 3). Overflow usually lasts less than two weeks.

Daily variations in flow correlate closely with temperature changes (Fig. 9). In 1971, for example, during the first two days of overflow (28-29 May) only about 6.5 m³ were discharged. On neither day did the air temperature rise above 0°C. However, on 30 May the temperature reached 7°C and the discharge

TABLE 3. Overflow characteristics

Year	Date flow began	Date flow ceased	Date of last snow or ice	Maximum discharge (litre/min.)	Total discharge (m ³)
1962	29 May	14 June	18 June	X	X
1964	X	3 June	15 June	X	X
1966	X	14 June	19 June	X	X
1971	28 May	9 June	14 June	20	62.3
1973	28 May	12 June	12 June	13	43.9

X — Not observed

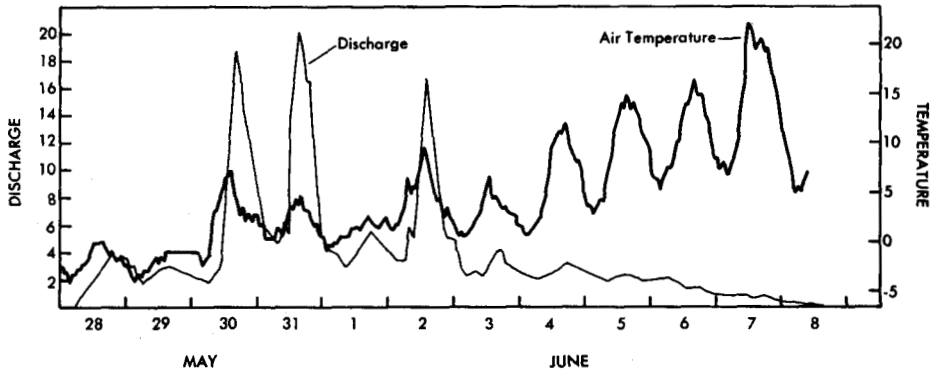


FIG. 9. Relation between air temperature ($^{\circ}\text{C}$) and pond discharge (litres per minute), 1971.

reached 19 litres per minute (total for the day over 10 m^3). The effect daily temperature has on overflow rates is well exemplified by records for 1 June. The temperature dropped below 0°C in the early morning and rose only a few degrees during the day. The overflow rate normally lags 1-3 hours behind temperature during high discharge and 4-5 hours during low discharge. The concentration of the bulk of the runoff within 2-4 days (Fig. 9) is representative in miniature of the regional hydrologic regime.

According to water-budget calculations for the basin for 1971, of the water available from snow and ice, 18% was lost by overflow and 45% by sublimation, evaporation, or percolation (Table 4). The amount of water perched in the basin at the end of the overflow period in 1971 was 126 m^3 , or 37% of the potential. The 153 m^3 loss, caused mainly by sublimation, appears reasonable in that actual calculation of the water equivalent of snow five days before drainage began (23 May) showed that a loss of 113 m^3 had already occurred (Table 2).

Summer and fall

The summer regime in the basin is considered to begin when overflow ceases, even though there may still be a small amount of snow present. The water resulting from the melting of this residual snow is compensated for by evaporation,

TABLE 4. Water budget, 15 May-9 June 1971 Putu Basin

	Vol. (m^3)	Total	Water equivalent (m^3)	Total	%	Total
Snow (15 May)	896		323			
Ice (15 May)	<u>21</u>	917	<u>18</u>	341	<u>100</u>	100
Overflow (total)	62				18	
Storage in basin at end of overflow period (9 June)	<u>126</u>	188		188	<u>37</u>	55
Loss resulting from sublimation and other processes			<u>153</u>	153	<u>45</u>	45

movement laterally in the sand, and reduction in volume accompanying the final melting of ice in the pond.

Drop in pond level during summer is quite constant, only slight variation and occasional reversals occurring. These changes correlate closely with temperature and precipitation. Temperature changes affect evaporation rates in the pond, and occasional rain and snow add small amounts of water (Fig. 10).

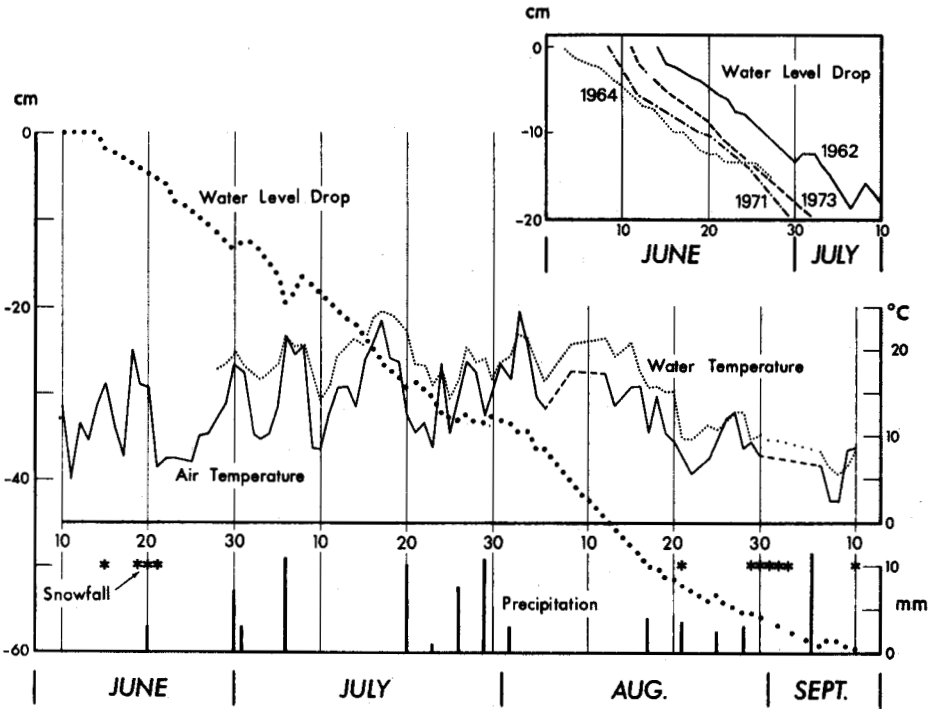


FIG. 10. Water level and weather conditions.

Variations in temperature with depth in the pond and in the sand occur throughout the summer (Fig. 11). The pond is shallow and generally nearly isothermal. Maximum temperature variation during the day in Putu Pond occurs at about 1800 hours. During 1971, the greatest variations recorded between the 5- and 50-cm depths were on the order of 6-7°C. The average difference was 3-4°C throughout most of the summer, although this difference decreased by mid-August. In early September, the gradient was reversed (Fig. 11C) when the surface water began to freeze.

Temperature in the sand follows somewhat the same pattern (Figs. 11B and 11D). The deeper in the sand the thermistor, the less rapid the change in temperature. Throughout most of the summer, the top layers of sand are warmer than the lower layers. During late August, however, air temperatures drop markedly, and sand temperatures follow suit. By early September 1971, the temperature throughout the sand column was nearly 0° C (Fig. 11D).

Throughout summer, a saturated zone around the edge of the pond persisted

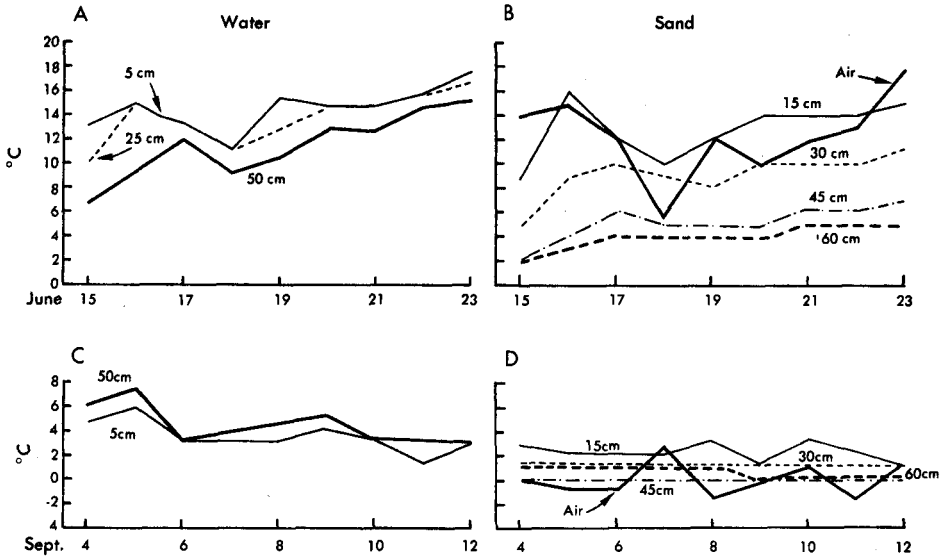


FIG. 11. Temperature profiles at various depths during summer and fall at 1800 hours.

because of capillary action. During rainless weather it varied in width to about 60 cm at the surface and tapered downward away from the pond toward the frozen surface.

DISCUSSION AND CONCLUSION

Putu Pond is one of the many intradune ponds found within the Colville Delta. It owes its existence to a combination of factors, the most important of which is permafrost. The annual cycle of these ponds is such that nearly all the geomorphic, hydrologic, and biologic activity associated with them is confined to 3-4 months of the year (Fig. 12). During this period planktonic growth of numerous species, especially among the crustacea, is rapid.

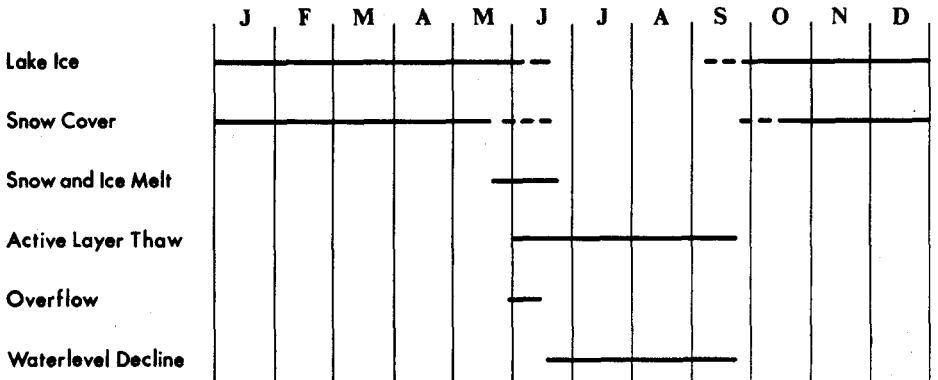


FIG. 12. Annual cycle of Putu Pond.

Although Putu Pond has been considered herein as a perennial pond, it is not a permanent feature of the landscape. Indeed, on almost any geomorphic time scale, it and all other intradune ponds are short-lived. In the case of Putu Pond there are at least two major processes leading to its extinction.

The first process is the headward erosion of the overflow drainage channel (Fig. 2). This channel, which has a vertical drop of more than 1.0 m at its head, is eroding at a rate of about 0.7 m per year. Most of this retreat occurs during the two weeks of overflow at the time of snowmelt.

The second process is the gradual filling of the pond by windblown sand. The nearly-complete vegetation cover over all but the steepest part of the basin, and the presence of water in the basin bottom, ensure that nearly all the sand that enters the basin is trapped. The unvegetated portions are on the steep southerly-facing portion of the basin (Fig. 4). In such a position the bare sand is protected from the prevailing (i.e., northeasterly) winds. The amount of sand added to the basin depends mainly on the strength and persistence of the wind during the snow-free period. During a series of windstorms in 1967 a 15-m² area at the eastern end of the basin was covered by a sand deposit that ranged up to 20 cm in thickness. The dunes northeast of Putu Pond are generally bare and are therefore excellent source areas (Fig. 2).

Although the two processes noted above are the major factors in reducing the longevity of the pond, the biota of the area are also significant. Upon drying, pond vegetation (Fig. 4) is added to the bottom. As the pond decreases in depth, water vegetation encroaches centreward. Squirrels are also effective agents because they bring to the surface much sand which moves downslope toward, and into, the pond.

Calculations based on data summarized in this paper show that Putu Pond will be drained before the year 2000.

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