Algae River: an extensive drainage system in the Bunger Hills, East Antarctica

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ABSTRACT An extensive terrestrial drainage system, centred on Algae Lake in southern Bunger Hills, is described. The 25-km-long Algae River is the third longest known in Antarctica after Onyx River (Wright Valley, Victoria Land) and Druzhby River (Vestfold Hills, Queen Elizabeth Land). Algae River receives meltwater from the Antarctic ice sheet, Apfel Glacier, and ephemeral and permanent snow banks in the ice-free area of the Bunger Hills. Water flows through a series of epiglacial lakes before reaching the extensive Algae Lake, which in turn has an outlet to Transkriptsi Gulf, a largely fresh-water, tidal epilake connected to the ocean under the Edisto Ice Tongue and Shackleton Ice Shelf. Total flow from Algae Lake was estimated to be greater than 1 x 10^6 m^3 s^-1 from data collected in the 1986/87 summer. Some portions of the drainage system were flowing during the 1946/47, 1985/86, 1986/87, 1994/95, 1995/96, and 1998/99 summers were not flowing during the 1999/2000 summer, indicating the variable nature of discharge in the river and emphasizing that parts of the drainage network may become disconnected readily.

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Introduction

Terrestrial drainage systems are relatively scarce in Antarctica, in part due to the small percentage of the continent that is ice-free. These systems are significant, however, because of the roles they play in biological, geochemical, and geomorphological processes, including species habitat and abundance (for example, Howard-Williams and others 1986; Vincent and others 1993; Niyogi and others 1997; McNab and others 1998), transport of nutrients and other chemicals (for example, Howard-Williams and others 1997; Lyons and others 1998), and sediment erosion and redistribution and the formation of fluvial landforms (for example, Selby 1971; Rainis and others 1980; Shaw and Healy 1980; Musley 1988; Gore 1992; Gore and Pickard 1998). Two Antarctic drainage systems have been studied in some detail: the Onyx River system in the McMurdo Dry Valleys (Chinn 1993 and hydrological reports referenced therein) and the Druzhby drainage system in the Vestfold Hills (Tierney 1975; Colbeck 1977; Adamson and Pickard 1986; Bronze 1996, 1999; Gore and Pickard 1998).

The main channel of Onyx River, the longest water course in Antarctica, flows from proglacial Lake Brownworth at the terminus of Wright Lower Glacier, inland to Lake Vanda, a distance of 28 km (Chinn and Dickson 1986). The source of the water in this system is mainly from the melting of glacier ice in the catchment (Chinn 1987, 1993), predominantly from the Wright Lower Glacier and Clark Glacier. The typical summer maximum instantaneous discharge of the stream at the Lake Vanda weir is approximately 2 x 10^3 m^3 s^-1 (Chinn and Dickson 1986), but it can reach 13 m^3 s^-1 (Chinn 1980; Anonymous 1984). Total annual discharge at Vanda weir is typically 4 x 10^5 m^3 (Chinn 1993), but that volume has been increasing during the last few decades (Howard-Williams and others 1997) and may reach 1 x 10^7 m^3 during some years (Chinn 1980). Chinn (1993) showed that the flow in the river was related to the number of positive degree days on the surface of the glaciers.

The Druzhby River drainage system has a more complex morphology and hydrology. Summer meltwater flows from the surface of the ice sheet through a series of lakes connected by short streams. Outflow occurs through Ellis Rapids at the head of Ellis Fjord, where Colbeck (1977) recorded a total annual discharge of 4.5 x 10^6 m^3, with a maximum instantaneous discharge of 2 x 10^3 m^3 s^-1. The total terrestrial portion of the drainage basin is about 25 km in length (Tierney 1975). Flow in this system is dependent on melting of the ice sheet and Siple Glacier, opening of meltwater channels on the ice margin, and sequential filling of the lakes in the various tributaries (Bronze 1996, 1999). All of the lakes in the system are ice-covered for 10–11 months per year, and ice (water) lost by ablation during winter and spring causes the lakes to fall below their outlet sills (Colbeck 1977; Bronze 1996, 1999). In this
sence the hydrologic behaviour of Druzby River contrasts with the Onyx, which has only shallow Lake Bull to fill along the 28 km from Lake Brownworth to Vanda well before discharge commences. Several of the Druzby River lakes are ice-dammed, and catastrophic decay of these barriers can lead to jökulhlaups (Gore and Pickard 1998). The existence of numerous, short gorges cut in sediment and bedrock by fluvial action in the Druzby drainage system (Adamson and Pickard 1986; Gore 1992; Gore and Pickard 1998) highlights the dynamism of this system and the importance of water as a geomorphological agent in Vestfold Hills.

This paper describes a previously unreported drainage system, here referred to as Algae River, in the southern part of the Bungar Hills, East Antarctica (66°10'S, 101°00'E; Fig 1). The Bungar Hills, which, at 952 km², is the largest ice-free oasis on the coastline of East Antarctica (Wisniewski 1983), is completely surrounded by ice: to the east are the Remenesh Glacier and the Antarctic ice sheet, to the south the Apsel Glacier, to the west the Scott and Edisto glaciers, and to the north the Shackleton Ice Shelf. More than 400 km² of the oasis is taken up by Cacapon Inlet, an area of marine water isolated (at least at the surface) from the Southern Ocean by the floating Shackleton Ice Shelf. The Bungar Hills sense stricto consists of a series of rugged, but low relief, islands, nunataks, and peninsulas. The largest continuous area of land is the southern portion, which has an area of 262 km² (Fig 1). The climate of the Bungar Hills is typical of East Antarctic coastal oases (Gregory 1980; Strenge 1986; Doran and others 1996), with air temperatures averaging above 0°C for approximately 6–8 weeks in summer. These temperatures, as well as direct solar radiation, result in considerable summer meltwater formation on the surface of the ice sheet and surrounding glaciers, as well as melting snow banks in the hills themselves. In many areas, meltwater from the ice flows towards the hills, where it typically accumulates in closed, ice-dammed epilaccol and tidal esphelc lakes along the rock–ice margin (Klokov and others 1990; Gal’chenko 1994; Klokov and Verkulich, 1994; Doran and others 2000). However, in the southeastern quadrant of the Bungar Hills, where

Methods

The drainage system was investigated during fieldwork in the Bungar Hills undertaken in the 1986/87 (EK), 1987/89 (EK), 1995/96 (DG), and 1999/2000 (IG) summers. In the first two seasons water level in Algae Lake was monitored at Oasis-2 Base (Fig 2), and several vane meter discharge rates were recorded in the outflow of the lake. Discharge rates on other occasions were calculated using a power function fitted to the data. Further water-level information for Algae Lake for the summer of 1987/88, 1989/90, and 1990/91 has been published previously (Klokov and Verkulich 1994). In the 1999/2000 season, all lakes along the southern margin of the Bungar Hills were visited, and their outlets traced. Information about other parts of the drainage system come from either observations made during the four field seasons, from aerial photography in February 1947 (Operation Highjump) or January–March 1986 (ANARE), or from two SPOT images acquired on 25 February 1990 and published by the Australian Antarctic Division at 1:50,000 scale.
Results

The Algae River drainage system in the southeastern quadrant of the Bunker Hills is dominated by Algae Lake and its outlet to Transkryptsi Gulf. Water is supplied to Algae Lake in four ways (Fig. 2):

- directly from the ice sheet via an extensive supraglacial drainage system;
- indirectly from the ice sheet, via intermediate lakes;
- indirectly from Apfel Glacier; and
- directly or indirectly via streams draining lakes fed from snow banks in the Bunker Hills.

These discrete systems, and Algae Lake itself, are discussed in the following five sections.

The name Algae Lake was proposed by the Americans after its discovery during Operation Highjump, and is accepted by both the US and Australian names committees. Algae Lake is often referred to in the literature as Figurnoye (or Figurnoe) Lake, a name conferred on it by Avsyuk and others (1956: 14), and accepted by the Russian names committee.

Direct input of meltwater from the ice sheet

Even though Algae Lake is bounded by rock for most of its shoreline, it abuts the ice sheet for approximately 400 m at its eastern extremity (Figs 2, 3). The plateau slopes down steeply to the lake in this region, and there are areas of supraglacial debris ('sheer' or 'inner' moraine; sensu Bishop (1957) and Weertman (1961), respectively) close to the ice–rock margin. The 1990 SPOT image shows melt streams that originate on the ice sheet up to 15 km east of the oasis and discharge directly into Algae Lake (Fig. 1). The melt streams that flow across the supraglacial debris mobilise the finely ground component of the glacial sediment and wash it into Algae Lake, forming conspicuous sediment-laden plumes (Fig. 3). While no estimates of discharge volume exist for these supraglacial streams, their length, the presence of large silt plumes in Algae Lake, and the noise of the waterfalls, which can be heard up to 10 km distant on quiet days, suggest it is substantial.

In contrast to the basin of Algae Lake abutting the ice sheet and those to the southwest (which clear progressively in the direction of flow in the lake), the water in Apelidki Inlet, the arm to the north-west of the region of Algae Lake bordered by ice cliffs, was observed to be clear in images recorded in 1947, 1986 (for example, ANARE CAS9543 frame 36), and 1990, and during fieldwork in 1988/89 and 1995/96. The authors infer that little of this silt-laden supraglacial meltwater flows into this arm of the lake.

Indirect input of meltwater from the ice sheet via intermediate lakes

Further streams from the ice sheet reach a series of small lakes along the margin of the ice sheet to the south of the section of Algae Lake that abuts continental ice (Fig. 3). Short channels connect these lakes to Algae Lake. Aerial photographs taken in 1947 show a major flow between Lakes 4 and 3 (Fig. 3), indicating that this could be an important water source for Algae Lake. It is possible that flow also occurs from other lakes in this region (including Lakes 1 and 5), although these areas have not been investigated in any detail on the ground. All of these lakes and the streams emanating from them appear highly turbid in the 1947 photography (for example, Lake 3), indicating significant meltwater input from the Antarctic ice sheet.
Examination of the 1947 aerial photographs and 1990 SPOT images reveals that there was a significant increase in the size and number of snow banks in this area during this 43-year period. It is possible that changes in the position and extent of snow and ice banks will result in interannual alterations in the route and volume of flows from these lakes into Algae Lake.

**Apfel Glacier drainage system**

In contrast to the eastern margin, most of the southern margin of the Flunger Hills abuts the relatively small Apfel Glacier. At the eastern end of the southern rock margin, the glacial ice slopes down to the land from the nearly flat surface of the glacier that lies 50–100 m above the rock of the hills. The altitude of the surface of the glacier decreases to the west, reaching the level of the rock approximately halfway along the southern margin of the hills. There is little or no moraine on the surface of the glacier in this region. A series of epiglacial lakes lie along the southern margin of the rock area. To the east, the surface levels of these lakes are well above sea level, and the lakes have outlets that flow into the hills, whereas farther west the lakes are close to sea level and typically do not have surface outlets. Of the epiglacial lakes that have an outlet, all but one drain ultimately into Algae Lake.

The outlet from the westernmost of the epiglacial lakes in this drainage system (Lake 11 in Fig. 2) flows via a small lake into the southwestern arm of Lake Burevestnik (maximum recorded depth: 55 m). The outlet from Lake Burevestnik is through an east–west aligned valley to Lake Ptichje. This valley was filled by ice and snow during both 1995/96 and 1999/2000 summers, and no flow was discernible. However, an interconnecting stream is clearly evident in earlier air photos (such as those from Operation Highjump), and water was flowing on 15 February 1987 to Lake Ptichje, which is at least 22 m deep (although probably much deeper), also receives water from a number of small lakes abutting the glacier (Lakes 8, 9, and 10) via short streams that flow either on the surface of the rock or under snow banks, in some places via other small lakes.

During the 1999/2000 summer, there was also direct input of glacial meltwater over a snow-covered bank of glacier ice to the south of the southernmost arm of the lake. Aerial photography shows that this area was free of ice and snow in 1947, with a gap a few hundred metres wide between the lake and the glacier ice. The outlet from Lake Ptichje is located at its easternmost point, and flows
Fig 4 Aerial view of Lakes 6, 7, and Dalekoje. Note the absence of suspended sediment in Lakes 6 and 7, which is in contrast to the turbid water of Lake Dalekoje. The outlet from Lake Dalekoje to the southeastern arm of Algae Lake is clearly visible. Note also the presence of suspended sediment in this portion of the lake, and the relative absence of sediment in the main portion of the lake at the top of the image. This implies that the sediment in the southeastern arm must have come from Lake Dalekoje. Photographs taken February 1947; the image is a composite of Operation Highjump Mission 19 Run 39 Image 203 vertical and oblique right.

through a narrow gully, down a 5-m drop in elevation, into Lake 7. Lake 7 is bordered by strongly rilled ice cliffs for a considerable distance on its southern side (Fig 4), and receives direct glacial meltwater input both from the ice surface and from subsurface melt of the ice. Figure 5 shows how Lake 7 melts and undercuts Apiel Glacier here, creating a minor cirque zone as the ice collapses into the lake. The outflow from this lake is via a short, narrow valley to the northeast into Lake 6, with a drop in elevation of only a few metres. Lake 6 also receives water from an extensive, permanent snow bank on its southern margin, but not directly from the Apiel Glacier or the Antarctic ice sheet. During January 1996, there was no outflow from Lake 6, as it was dammed by a large, permanent bank of snow and ice on its eastern shore. However, during January 2000, outflow to Lake Dalekoje occurred via a tunnel through the snow and ice bank. This ice feature was also present in 1947 (see Fig 4), and January 1986 (CAS9502 frame 39 and CAS9507 frame 37), although it was much smaller than in 2000. The outflow in 1947 also
Flow through these lakes in both 1995/96 and 1999/2000 summers was limited, indicating that little meltwater from the Apfel Glacier was entering the system, and it is probable that at no time is this part of the drainage system a major source of water for Algae Lake. This conclusion also stems from the topography of the glacier in this region. The ice slopes up steeply from the land margin to a flat ridge a few hundred metres from the rock. To the south of this ice ridge, the glacier surface slopes down gradually southwards, away from the Bunge Hills and toward the moraine line between the Apfel and Scott glaciers. Thus, most of the surface flow is diverted into an extensive supraglacial drainage system, and the area of the glacier that drains to the landward side of the divide is limited. All of the lakes along the southern margin of Bunge Hills show little, if any, evidence of the input of silt-laden glacial meltwater (Fig. 4), consistent with the absence of supraglacial debris along the northern margin of Apfel Glacier. It is possible that some sub-glacial flow carrying sediment enters these lakes at depth. However, the slope of the glacier away from the land suggests that the bedrock has a similar topography, limiting sub-glacial input. Furthermore, mixing within these lakes resulting from solar heating and heat loss to the marginal glacier would be expected to distribute any sediment throughout the water column. The apparent absence of sediment in the surface waters of these lakes indicates that any such input is minor.

Lake Dalekoje also abuts the ice margin, but in contrast to the lakes in the upstream portions of this drainage system, the ice is part of the ice sheet rather than the Apfel Glacier. The lake is markedly different to the other epiglacial lakes, in that it is highly turbid (Fig. 4) as a consequence of silt washing in from the supraglacial debris on the ice sheet. Like the streams that flow into the eastern embayment of Algae Lake, a 15-km-long supraglacial stream system, visible in the 1990 SPOT image, flows from the ice sheet into Lake Dalekoje. This lake, which is at least 70 m deep (Klokov and Verkulich 1994), drains via a narrow valley that extends from the western extremity of the lake to the narrow southeastern arm of Algae Lake. When visited in January 1996 and January 2000 the floor of this valley was covered by an extensive snow bank, and no evidence of sub-nival flow between the lakes was observed. This snow bank was also
present in February 1990 (SPOT image), although it is impossible to determine if there was any water flow through this valley at that time. In contrast, the 1947 aerial photographs (Fig 4; also see Byrd (1947) for a colour image looking from above Algæ Lake towards Lake Dalekoje) show that the valley was largely snow-covered, and that there was clearly a plume of turbid water entering the southeastern arm of Algæ Lake from Lake Dalekoje. As discussed above, it appears that the ice in the outlet valley from Lake Dalekoje creates a snow or ice dam that fails in some summers, resulting in a jökulhlaup and rapid flow of water into Algæ Lake.

Land-based drainage systems

There are three significant, entirely land-based drainage systems that reach Algæ Lake, in addition to a host of smaller drainage lines (Fig 2). The first stems from Lake 12, which is located to the north of a major snow bank/ice system at the centre of the southern margin of the Bunker Hills, but which does not contact Apfel Glacier. An outlet stream flows down a well-defined valley to Algæ Lake, terminating in a well-formed delta. The second consists of a string of lakes, the highest of which (Lake 13) is in contact with an extensive snow bank contiguous (at least in January 2000) with glacial ice. However, the topography of the area is such that melt from the glacier would not enter Lake 13, but rather would reach a depression at the junction of the snow bank and the glacier. The outlet from Lake 13 passes through three intermediate lakes before reaching Algæ Lake, again terminating in a well-formed delta. The third system flows from the western end of Lake 14: a lake high in an east–west aligned valley located well away from the glacier, passing through a small lake before reaching Lake Dolgoe. Lake Dolgoe, 6 km long but no more than 500 m wide, has a maximum depth of 60 m (Klokov and Verkulich 1994), and is fed solely by snow melt in its catchment. The Lake Dolgoe outlet stream at the eastern end of the lake flows a short distance over glacial sediment directly into Algæ Lake. Aerial photography (1947 and 1986 CAS9542 frame 37) and direct observation (21 and 28 January 1987, 15 and 20 February 1988, 19 February 1989, and January 1995) indicated strong outflow from Lake Dolgoe, but on 16 January 2000 no outflow was observed. The flow was estimated to be 0.5 m³ s⁻¹ on 21 January 1987. Algæ Lake also receives limited meltwater input directly from snow banks in its catchment. There are numerous other small affluents that contribute to Algæ Lake along short drainage paths. In a number of places, glacifluvial canyons link small lakes to Algæ Lake. One example lies on the south shore of Algæ Lake north of Lake Burevestnik: there, a snow bank–dammed lake about 50 m in diameter lies immediately above a narrow (10 m), deep (15 m), and short (<50 m) canyon that is glacifluvial, and not glacial, in origin (Fig 6; compare with Olvmo 1992; Gore and Pickard 1998). The authors believe that the canyon probably formed when the ice edge was closer and meltwater was much more abundant, because present-day flows from the small lake are clearly not powerful enough to pluck the bedrock and transport large boulders into Algæ Lake. Inheritance of glacifluvial features and flowlines is manifest in other areas of the Algæ River system, such as the large boulder-covered alluvial fan described below from the Algæ Lake outlet.

Algæ Lake

Algæ Lake is one of the larger (14.3 km²) and deepest (145 m) lakes of the oases that occur around the coast of Antarctica (Klokov and Verkulich 1994). The lake’s morphometric parameters compare with 7.1 km² (Lawrence and Hendy 1985) and 20 m deep (Spigel and Prikge 1998) for Lake Fryxell, the largest lake in the McMurdo Dry Valleys; 8.3 km² and 138 m for Crooked Lake in the Vestfold Hills (Brommge 1996); 19.9 km² and 362 m for Radok Lake in the Prince Charles Mountains, which is the deepest lake known on the surface of the Antarctic continent (Ward and others 1988; Bard and others 1990); and 11.4 km² and 169 m for Lake Untersee in the Wollbach Mountains in Dronning Maud Land (Ward and others 1997). The morphology of Algæ Lake is strongly controlled by three intersecting fault systems, aligned approximately 0°–180°, 80°–260°, and 120°–300°, that have formed a number of deep basins separated by relatively shallow connections. The lake is ice-covered for approximately 10 months of the year, becoming largely ice-free in late January or early February.

The outlet to the lake is at its western extremity, where a stream flows through a narrow, steep-sided valley across a boulder-covered alluvial fan to Izviliusta Inlet, the easternmost extension of Transkriptsi Gulf (Fig 2). The outlet stream from Algæ Lake was not flowing when visited in January 2000, but flow had occurred in the 1998/99 summer (M. Sharp, pers. comm. 2000), 1995/96, 1994/95, 1986–91 (Klokov and Verkulich 1994), 1985/86 (CAS9507 frame 37), 1976/77 (Barker 1977), 1946/47, and presumably many other years. During December 1995, at the very start of outflow from Algæ Lake, an extensive river naled (compare Grigor'ev 1960), consisting of frozen water from the end of the previous melt season, lay across approximately 250 x 80 m of the alluvial fan at the base of the outlet valley, covering even the largest boulders (Fig 7). A similar naled was present in January 2000.

The flow rate of the outlet of Algæ Lake was measured on seven occasions in January–March 1987, and was found to be related to the water level of the lake by a simple power function (Fig 8). The water level of Algæ Lake was monitored on a regular basis between 19 January and 12 March 1987, allowing integrated estimates of discharge to be made. Figure 8 shows that when measurements were begun discharge was approximately 2 x 10⁶ m³ d⁻¹, a rate that was maintained until late in the month. From 31 January 1987 a sharp increase in the flow occurred that was associated with a 16 cm rise in the water level of Algæ Lake. Subsequently, flow decreased steadily until the end of the study.

The total flow during the monitoring period was
estimated to be $1.0 \times 10^7$ m$^3$. This estimate does not take into account flow either before the 19 January 1987 or after 17 March 1987, and therefore should be considered a lower bound for the total discharge of the system in that year. Comparison to other summers suggests that flow would start in early to mid-January, and continue until early April (Klokov and Verkulich 1994), yielding an estimated total flow for the 1986/87 summer of $1 \times 10^7$ m$^3$ (Fig. 8).

The rapid increase in water level in Algae Lake and flow in Algae River at the end of January 1987 was attributable to the catastrophic decay of an ice dam blocking the exit of Dalekoje Lake. When visited on 12 March 1987 this lake was surrounded by remnants of ice clearly derived from a previous lake-ice cover well above the observed surface ice level (Fig. 9); the lake surface was covered by a layer of new ice 0.24 m thick, and no water was flowing from the lake. The height difference between the ice layers was 5.5 m, indicating a marked and rapid decrease in water level sometime during the preceding months. Assuming an area for Lake Dalekoje of 0.4 km$^2$, $2.2 \times 10^6$ m$^3$ of water was discharged at the time of the ice-dam failure. This corresponds closely to the $2.3 \times 10^6$ m$^3$ of water required to increase the level of Algae Lake by 16 cm. If the discharge occurred over a period of two days (as indicated by the length of the period during which the level of Algae Lake increased), the average discharge rate was $13$ m$^3$ s$^{-1}$, which is similar to the $8$ m$^3$ s$^{-1}$ measured after similar ice-dam collapses in the Vestfold Hills by Gore and Pickard (1998).

A rapid increase in the water level in Algae Lake of similar magnitude also occurred on 22–23 February 1989, suggesting a further catastrophic discharge from Lake Dalekoje (although it is possible that the water came from other ice-dammed lakes, such as Lake 6). Similar discharges did not occur in the intervening summer, nor in 1988/89 (Klokov and Verkulich 1994), indicating a two-year periodicity in the failure of ice dams in the drainage system during this period.

Transkriptsii Gulf is a tidal epishelf lake (Klokov and others 1990). Although it is not a marine system in the sense that it is largely fresh water, it is marine in that a hydraulic connection to the sea clearly exists: it is tidal, and it contains saline water at depth. Therefore the Algae River drainage system can be considered to be externally draining.

**Discussion**

The terrrestrially based drainage system described in this
paper, from Lake 11 to Transkriptsiul Gulf at the outflow from Algae Lake, extends for approximately 25 km, making it one of the longest drainage systems in Antarctica. If the ice-based extension to the east is included, the length increases to 30–35 km. Druzhby River in the Vestfold Hills is similar in that it drains a portion of the ice sheet and adjacent Sør Rondane Glacier (Tierney 1975; Colbeck 1977; Bronger 1996), although it is slightly longer than Algae River. Both of these rivers are characterised by similar features: most of the water flow is derived from the ice sheet or glacier; short streams connect large lakes along the main line of drainage; flow of water occurs under snow banks and ice that may result in damming of streams and catastrophic discharge from time to time (Gore 1992; Gore and Pickard 1998); and a large lake integrates flow from smaller lakes located close to the ice–rock margin. While approximately 75 km² of the ice sheet drains into Algae Lake, it is difficult to calculate the total area of the drainage basin, particularly the terrestrial portion. As pointed out by Bronger (1996), most of the small lakes in nominal Antarctic drainage basins are in fact closed, and do not contribute to the drainage, and therefore should not be considered part of the basin. If water balance in the area were to increase dramatically, however, outflow from all of these lakes would eventually reach Algae Lake.

The estimated discharge for the Algae River system for the 1987/88 summer, 4 x 10⁶ m³, was of a similar magnitude to discharge from Ouyx River (0–1 5 x 10⁶ m³, typically 4 x 10⁴ m³ at Vanda weir (Chinn 1993)), and for Druzhby River (2.7–4 5 x 10⁶ m³ at Ellis Rapids (Colbeck 1977; Bronger 1996)). The ice sheet to the east of Algae Lake is probably the major source of water for the system. No direct observations of these streams were made during this study, but during January 1996, waterfalls flowing from the ice sheet and entering Algae Lake and other lakes along the margin of the ice sheet were heard from 8 km and later observed from 2 km distance. The input from Lake Dalekoje and the Apfel Glacier system can be estimated at 10⁶ m³ s⁻¹ (assuming that the water lost from Dalekoje Lake in January–February 1987 represented two years build-up, and that the flow that occurred after the ice-dam failure was insignificant), which represents only approximately 10% of the estimated total system discharge. The amount of water input into the system by the Apfel Glacier portion of the drainage is therefore likely to be very small, as direct flow into Lake Dalekoje from the ice sheet is probably significant. This is consistent with only a small portion of the surface of the glacier draining into the Algae River system, and with the low water flow (in the order of litres per second) from Ptich'je Lake to Lake 7 in January.
Fig 8 Calculated average daily discharge rates for Algae River downstream from Algae Lake. The inset shows the relationship between water level at Oasis-2 Base and river flow used to calculate discharge. See the text for discussion of the methods used.

2000, and only slightly higher flows in connections farther downstream.

The absence of flow in the Algae River during January 2000 does not necessarily imply that no flow occurred in that summer. Even though observations were made during the warmest part of the year, flow from Algae Lake could have occurred later in the season, as in previous years. Water is lost from the ice surface of lakes by ablation during winter and spring, so that many lakes fall 0.5–1 m below their outlet sill. The first inflow of the melt season is spent refilling the lake basins before outflow to the next lake downstream can occur. For Algae Lake, a 0.5–1 m drop in level due to ice ablation is equivalent to a loss of water of $7.2-14.3 \times 10^6 \text{ m}^3$. This volume is in the same order of magnitude as the estimated outflow from Algae Lake, indicating that perhaps 50% of the input into the lake goes to increasing the water level to the outlet sill. A similar occurrence has also been noted in the Druzhby River drainage system at Vestfold Hills (Colbeck 1977; Bronge 1996; Gore and Pickard 1998), when the downstream portions of the drainage system did not begin flowing until well after those closer to the ice sheet or glacier.

Hydrologically, there are interesting comparisons between Algae River and the more completely studied Onyx and Druzhby rivers. Algae River is similar to Druzhby River in drainage-basin physiography, the dominance of large lakes in their catchments, the occurrence of jökulhlaups, and the presence of extensive areas of ice sheet and glacier ice. However, Algae River, like Onyx River, has significant interannual variation in discharge. While albedo change due to heavy snows can prevent the Onyx from flowing (Chinn 1983), the authors infer that cooler than normal temperatures can prevent Algae River from flowing. Interestingly, Druzhby River has always been known to flow, despite seasonally cool temperatures or heavy snowfalls. The contrasting hydrologic behaviour of these three rivers illustrates that there is still much work to be done before the nature of melt and runoff, and their attendant controls on oasis biology, geochemistry, and geomorphology, are known.

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References

Adamson, D. A., and J. Pickard 1986
Geographical observations in an Antarctic ‘oasis’ Moscow: USSR Academy of Sciences.
Bardin, V.I., A.A. Piskun, and N.A. Schmiedsberg 1990
Gidrologo-gidrokhimicheskaya kharakteristika gubokovodnykh vodoemov v gorakh Prins-Charles [Hydrologic and hydrochemical characteristics of deep water bodies in Prince Charles Mountains]. Antarktika 29: 97–112.
Bishop, B.C. 1957
Shear moraines in the Thule area, north-west Greenland Wilmette, IL: US Army, Corps of Engineers (SIPRE Research Report 17).
Bronge, C. 1995
Hydrographic and climatic changes influencing the proglacial Druzhby drainage system, Vestfold Hills, Antarctica. Antarctic Science 8: 379–388.
Bronge, C. 1999
Chinn, T.J. 1980
Chinn, T. J. 1983
Chinn, T. J. 1993


Weertman, J. 1961. Mechanism for the formation of inner moraines found near the edge of cold ice caps and ice sheets. Journal of Glaciology 5: 287–303