Modeling of Active Layer and Runoff: A Case Study from Small Watersheds, Kolyma Water Balance Station

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Abstract

Hydrological processes taking place in the Arctic have some distinctive features related to permafrost and the active layer. The goal of this research is to verify the algorithms of the "Hydrograph" hydrological model in permafrost regions. Verification is based on the data derived from the runoff observations and progression of the active layer at the Kolyma Water Balance Station (KWBS). Analysis of the KWBS observation materials indicated that the active layer thickness varies across a wide range within a limited territory and depends on the landscape type. This research identified three major landscape types, which differ considerably in the regime and progression of active layer formation. They are stone taluses (golets), tundra open woodland, and swamp larch forest. The systematization of the properties of their soil and vegetative covers made it possible to assess the values of the "Hydrograph" model parameters without the application of calibration methods. The active layer dynamics and the dynamics of the runoff formation were jointly modeled for the KWBS venues using the same set of values of the model parameters. The estimated maximum thawing depths were in satisfactory accordance with the observed data. However, the estimated start of freezing occurrence is considerably later than the observed one. Analysis of the results of the runoff hydrograph modeling indicated that those model algorithms that describe the process of water filtration into frozen ground during the snow-melting period do not reflect natural processes adequately enough and require further development. This is caused by the fact that the role of the surface runoff during snow-melt is exaggerated, while the amount of water that percolates through the soil and freezes in it is underestimated. The results of runoff modeling in the summer period under the conditions of a thawed active layer are evaluated as satisfactory. This paper shows the importance of observation data for the improvement of the runoff formation models in the permafrost zone. The situation can be considerably improved by reestablishing monitoring at the Kolyma Water Balance Station.

Keywords: active layer; "Hydrograph" model; Kolyma Water Balance Station; permafrost; runoff formation.

Introduction

The arctic hydrologic cycle, which is currently being exposed to the influence of both climate change and anthropogenic disturbances, is the subject of numerous investigations. Permafrost is one of the major factors in runoff formation in the polar regions.

Active layer formation essentially depends on the properties of a particular landscape. The difficulty of studying hydrological processes lies in the need to consider the energy component of the hydrologic cycle. For instance, the heat balance of permafrost determines the following processes: water infiltration into permafrost, formation of permafrost aquiclude, water exchange between surface and subsurface waters, and seasonal runoff redistribution due to freezing of liquid precipitation or the melted water in the ground.

Our knowledge of arctic hydrologic processes remains incomplete, and that is why mathematic formulas presented as models of various processes are developed and tested based on the data produced by field observations.

Many researchers work to develop a physically based distributed hydrological model that describes the energy and moisture dynamics under conditions of a certain watershed at the required level of detail. This is made to estimate river runoff characteristics and evaluate the variable states of a permafrost zone basin.

For instance, Canadian researchers (Pomeroy et al. 2007)

worked on the design and improvement of the physically based Cold Region Hydrological Model (CHRM). The CHRM describes in detail such processes as snow accumulation, wind-blown snow redistribution, snow melting (with the employment of energy balance equations), water infiltration into permafrost, and evaporation. The peculiarity of the approach suggested by the Canadian scientists is that the model parameters are not calibrated in the course of calculations. Presently, the CHRM offers only a limited opportunity for estimating the runoff from the territory of the whole basin, despite the fact that it has an elaborate algorithm for hydrological process modeling at a specific point.

The US investigations of the runoff formation processes in permafrost regions are carried out in Alaska. A deterministic distributed model, ARHYTHM, was developed for the basins of the Kuparuk and Imnavait rivers based on field research aimed at the description of thermal and hydrological processes in the arctic territories (Zhang et al. 2000). The ARHYTHM authors revealed the hydrological importance of such processes as phase transitions in soil, snow melting, summer evapotranspiration, and formation of the active layer.

Russia has long-term experience in special hydrometeorological observations in the network of water balance stations located in various geographical zones of the country.

The Kolyma Water Balance Station (KWBS) located in the upper reaches of the Kolyma River is unique for mountainous permafrost areas. A wide range of special observations have been conducted there since 1948. The data collected at the station were applied to develop, test, and improve hydrological models multiple times (Gusev et al. 2006, Kuchment et al. 2000, Semenova 2010).

Our country's research experience in the field of runoff modeling in permafrost areas (Gusev et al. 2006, Kuchment et al. 2000, Semenova 2010) indicates that temperature changes and phase transitions in soil exert a significant influence on hydrological processes. They determine the possibilities of water infiltration into soil and the formation of surface, soil, and underground runoffs.

The "Hydrograph" hydrological model used in this research was applied multiple times in estimating runoff in the polar regions (Pomeroy et al. 2010, Semenova & Vinogradova 2009, Vinogradov et al. 2011, Lebedeva & Semenova 2011). The calculations presented in these investigations made it possible to conclude that the "Hydrograph" model, in case its algorithms are further developed, will have a great potential to be applicable in both research and practical tasks in permafrost zones, including watersheds that partially or totally lack observation data.

Goals and Objectives

The need to consider the influence of permafrost on hydrological processes leads to the fact that the algorithms utilized in models must be capable of functioning both under permafrost conditions and outside them. To meet this requirement, they must be based on general physical principles of runoff formation instead of local empirical relationships. The deterministic distributed "Hydrograph" hydrological model employed in this research was constructed on these principles (Vinogradov 1988, Vinogradov & Vinogradova 2010).

According to the physically based approach, active layer formation as well as runoff formation at a watershed should be described by means of one and the same set of values of the model parameters. This becomes possible if the physical properties of landscapes (measured in the field) are used as parameters.

The goal pursued in this research is to verify the algorithms of the "Hydrograph" hydrological model in permafrost areas employing the data of the observations over the runoff and over variable states of the active layer.

The following procedures were carried out to achieve this: analysis of seasonal thawing depths of ground under different conditions at the Kolyma Water Balance Station (KWBS), systematization of landscape properties, determination of model parameters, and estimation of the thawing depth as well as the runoff.

A small watershed of the Kontaktovy Stream (21.6 km²) at KWBS was selected as a research target.

The systematization of the parameters describing the thawing process and runoff formation under the given natural conditions allowed us to use the values of these parameters to model water discharge in four larger basins under similar conditions in northeastern Russia (Semenova & Lebedeva 2012). The modeling process is facilitated by the fact that

the conditions of the Kolyma station are representative of the extensive territory of northeastern Siberia (Boyarintsev 1988).

The "Hydrograph" Model

The "Hydrograph" model is a deterministic hydrological model with distributed parameters. It describes runoff formation processes based on their physical features.

The concepts that form the basis of the modeling scheme and its algorithms are described in detail in the works following Vinogradov (1988), Vinogradov & Vinogradova (2010), and Vinogradov et al. (2011). A description of the "Hydrograph" model in these collected works may be found in the paper by Semenova & Lebedeva (2012).

The major advantages of the "Hydrograph" model are:
- universality (i.e., the opportunity to apply it to basins of any size without changing model structure);
- use of physical properties of landscapes observed in nature as the model parameters;
- use of data of standard meteorological observations (precipitation, air temperature, and air humidity deficit) as input.

The mathematical description of runoff formation processes of the model includes canopy interception; snow cover formation; snow melting and snowmelt release; surface retention; soil heat and moisture dynamics; formation of surface, soil, and underground runoffs; and evaporation and transformation of surface and channel runoffs.

The concept of runoff elements used in the "Hydrograph" model for spatial discretization of basins is one of the key ones. The basin territory is divided into several conditionally homogeneous parts called runoff elements. It is assumed that the characteristics of soil, vegetation, relief, and other components of the landscape are constant within each runoff element, while the runoff formation process is uniform. A considerable part of the model parameters is determined separately for each runoff element and in this way they are being systematized.

Materials

General information on KWBS

The Kolyma Water Balance Station (KWBS) is located in the upper reaches of the Kolyma River in the zone of continuous permafrost. Standard as well as special and experimental hydrometeorological measurements were carried out at the station from 1948 to 1997. Special and experimental measurements included the monitoring of the active layer formation, snow measuring surveys at different landscapes, monitoring of evaporation on various underlying surfaces, and others (Fig. 1) (Observation materials... 1948–1990). Water balance observations were suspended at the KWBS since 1997. Only meteorological observations and runoff observations at seven streams are presently carried out.

The local relief is mountainous. The slope height varies from 800 to 1700 m. The mean annual air temperature in the period from 1950 to 1990 was -11.6°C, and the annual precipitation sums ranged from 250 to 440 mm (Zhuravin 2004).
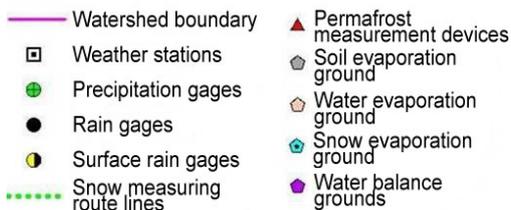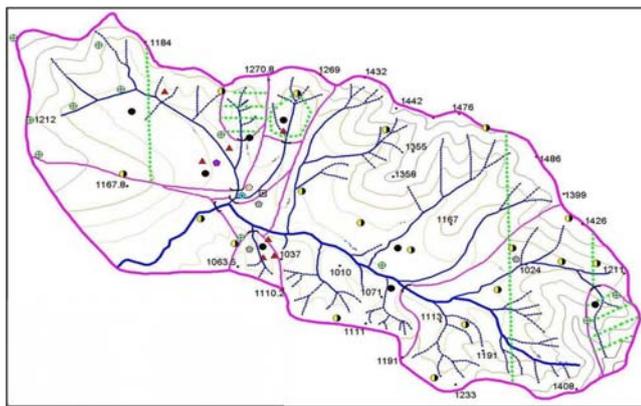
Figure 1. Map of the Kolyma Water Balance Station.

Figure 2. Major landscapes on the territory of the KWBS.

The KWBS landscapes

Six major types of landscape are found at the KWBS according to Korolev (1982): golets (stone taluses), mountain tundras, moss and lichen larch open woodland, thickets of cedar elfin wood, sparse larch forests with bushes, and swamped sparse stands of larch with bushes.

Relying on this classification as well as on the description of soils, vegetation, and geological structure, and on other information that accompanies the data provided by observations, it is reasonable to distinguish three runoff elements: golets (stone taluses), tundra open woodland, and swamp larch forest (Fig. 2).

Golets occupy the upper and steep parts of slopes where only crustose lichens grow. Mountain tundras and open woodlands are spread in saddles as well as in the middle parts of slopes. Sparse larch trees, cedar elfin wood, moss, and lichens grow here. Swamp larch forests occupy flat valleys and terraces.

The active layer observations

Approximately 20 permafrost measurement devices (thaw tubes) were in operation at the KWBS in different periods of time. Their period of observations ranged from 3 to 25 years.

Analysis of the data given by observations over the dynamics of soil thawing and soil freezing indicated that active layer depth exhibits considerable variability across the station's territory and depends mainly on the type of landscape. Figure 3 illustrates soil profile characteristics of two different landscapes and their typical progressions of thawing and freezing.

The maximum depth of the active layer registered during the entire observation period at KWBS was 1.7 m, while according to the expedition data by Bantsekina (2003) it reached 2.3 m. Such depths are typical of golets with undeveloped soil profile and no vegetation (Fig. 3). Water easily seeps through rock debris down to the aquiclude formed by the permafrost table and rapidly flows down into a channel. Thus, dry conditions are created. The minimum
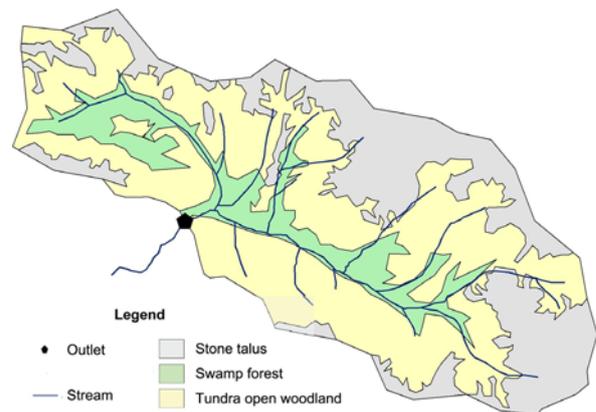
thawing depth (.6 m) is observed in swamp forests with a considerable peat layer in their soil profile (Fig. 3) and soil surface covered with a moss layer, which impedes heat exchange and favors the development of moist conditions.

The runoff observations

Water discharge was measured at nine watersheds of the KWBS with the area ranging from 0.27 km^2 to 21.6 km^2 and the mean heights ranging from 985 to 1370 m. Boyarintsev (1988) notes that small watersheds at the KWBS reflect local peculiarities of the runoff formation that are typical of certain landscapes, while larger basins are representative of the entire region's territory.

When the soil begins to thaw directly after snow melting in spring, melt waters form a surface runoff everywhere except for the territories occupied by golets. A considerable part of melt water percolates through the frozen ground and freezes. This ice constitutes an additional source of water in summer; that is why runoff is observed in the warm season even when precipitation does not fall for a long time (Boyarintsev 1988). The described process of seasonal water distribution is most developed in the golets area where almost the whole volume of melt water seeps into the ground.

Results

The active layer modeling

Two permafrost measurement devices (thaw tubes) reflecting the peculiarities of two major types of soil thawing were selected to model the active layer depth. One of them is installed at the slope of the southern aspect in the golets zone at the height slightly above 1000 m, while the other is located within a swamp forest of the stream valley at the height below 900 m. The observation data covering the period of 1977–1978 are available for the permafrost measurement device in the golets zone, and the data of the period from 1980 to 1984 are available for the second device in the swamp forest.

Physical properties of soils and of vegetation are the main parameters of the "Hydrograph" model that determine soil moisture and heat dynamics. Twenty estimated soil layers (ESL) with the thickness of 10 cm were distinguished in each soil profile to perform estimations. Each estimated soil layer is characterized by a set of parameters that reflect both its thermal and hydrological properties. The values of the

Table 1. The values of soil parameters of the "Hydrograph" model.

	P, DQ	D, kg/m^3	HC, J/kg*°C	TC, W/m*°C	MWRC, DQ	IC, mm/min
Moss	0.80	900	1930	0.5	0.60	10
Peat	0.80	1750	1930	0.8	0.50	0.3
Clay with rock fragments	0.50	2650	750	1.7	0.15	1
Stone talus	0.55	2600	750	2.3	0.13	1.8
Parent rock	0.50	2650	750	2.3	0.13	1.8

See the notation in the text

parameters were determined based on literature as well as on the description of soil profiles that accompanied observation materials (Observation materials... 1959-1991, Guide... 1988, Bantsekina 2003).

Table 1 presents the values of such parameters as porosity (P), density (D), maximum water retention capacity (MWRC), infiltration coefficient (IC), thermal conductivity (TC), and heat capacity (HC). These values characterize soil layers in the dry state.

According to the observation materials at the KWBS (1959–1990), the active layer is in the air-dry state by the time it is covered by snow in autumn. Meanwhile, all the ground pores below it are filled with ice. Based on this, the initial values of ice content in 6 upper ESLs of a swamp forest and in 16 ESLs of the golets area were determined as equal to the values of their maximum water retention capacity, while in the lower ESLs they equaled the porosity values.

Estimates of both the moisture content (ice content) and the temperature in an ESL are done simultaneously. Meanwhile, the values of infiltration coefficient, thermal conductivity, and heat capacity of an ESL are specified according to the moisture content (ice content) in the layer.

The maximum water retention capacity varies in a wide range from 0.13 in the golets area to 0.50 in the peat horizon of soil of the swamp open woodland. Thermal conductivity takes values from 2.3 to 0.8 W/m*°C, while heat capacity takes values from 750 to 1930 J/kg*°C in the soils of golets area and those of forest, respectively.

Figure 4 shows a comparison of the estimated and the observed active layer depths for the selected permafrost measurement devices. The maximum thawing depth measured is in good agreement with the maximum thawing depth calculated. However, freezing according to the model estimates occurs considerably later, as compared to the observation data. The assumed reason for this is that the estimated heat-insulating influence of the snow cover in autumn was significantly exaggerated.

The runoff modeling

The runoff of the Kontaktovy Stream (the area is 21.6 km^2) was modeled for the period from 1971 to 1984. The values of soil and vegetation parameters used were the same as in the estimates of the active layer depth. Figure 5 shows

a comparison of the observed and the estimated runoff hydrographs for the period of 1981–1982.

The observed mean annual runoff was 287 mm for the modeling period of 14 years, while the estimated mean annual runoff was 220 mm. The mean error is 24%. The maximum difference between the observed and the estimated values of annual runoff reached 49% in 1983, which was one of the driest years (precipitation sum was only 307 mm). This is attributed to the fact that the absolute errors in dry years exerted a more considerable influence, which increases the relative error. The errors less than 20% are observed in wet years (e.g., 1972, 1975, 1977, 1979, 1981, and 1984). Overall, the model slightly underestimated runoff.

As Figure 5 shows, the maximum deviation of the estimated water discharge from the observed water discharge occurs during the snow-melting period of the year. According to the estimates, all the melt water forms a rapid surface runoff above the soil that is still frozen, including the golets territory (40% of the watershed's area). Therefore, the flood reaches a high peak directly by the end of snow-melting period. The research by Bantsekina (2003) based on the field study at the experimental site of the golets zone at the KWBS shows that all the water produced at the beginning of a snow-melting period freezes in the active layer and forms infiltration ice. Channel runoff starts only when 90% of the seasonally thawed layer heats above 0°C.

The calculated and the observed hydrographs are in good agreement with each other in the second half of summer as well as in autumn.

Soil moisture content plays an important role in the permafrost zone; it both accumulates water at a watershed and regulates such moisture and heat flows as evaporation and phase transitions in the active layer (Hinzman et al. 2003). It is still an important task to integrate the calculation algorithms of soil thawing and water infiltration into frozen ground into hydrological models. Despite the fact that such algorithms were designed to approach specific tasks (Arzhanov et al. 2007, Kudryavtsev 2004, Perlshteyn 2009), only a few efforts were made to directly incorporate the description of these processes into hydrological models (Gray et at., 2001, Kuchment et al. 2000, Zhang et al., 2008), including the "Hydrograph" model (Vinogradov et al. 2011). The major difficulty encountered in the permafrost zone is to implement such hydrological properties of soil layers as the maximum water retention capacity and the infiltration coefficient in the process of water phase transitions. Conceptualization of these processes in modern models relies more on the data from empirical observations. For instance, in the research of Lebedeva & Semenova (2011), the comparison between the algorithms that describe the water infiltration processes into frozen soil and the algorithms that are used in the CRHM model (Pomeroy et al. 2007) and in the "Hydrograph" model was made (Vinogradov et al. 2011). The comparison indicated that similar results in runoff estimates may be obtained when conceptually different approaches are employed. According to the authors of this research, the basis for the accomplishment of the set task may be formed only if the data of the observations over soil moisture content and runoff at small watersheds with uniform landscape parameters are jointly analyzed, while the measured hydrological properties of soil are simultaneously systematized.
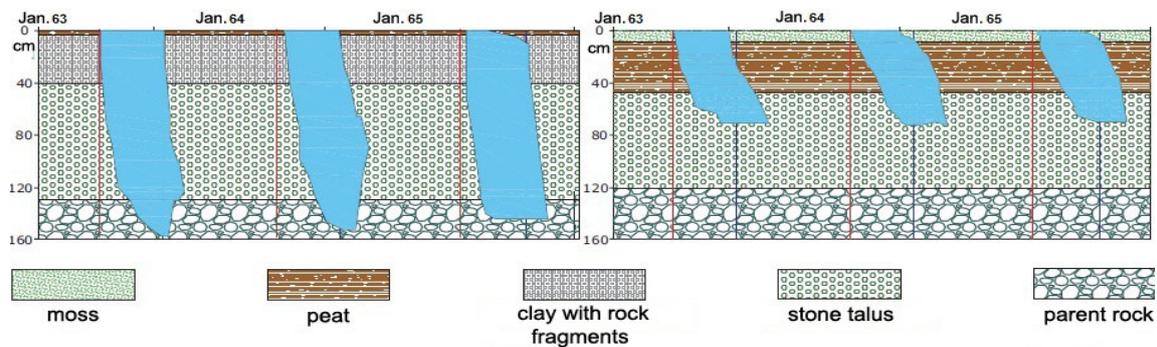
Figure 3. The soil profile and the typical thawing process in the stone talus (on the left) and in the soils of a swamp forest (on the right).
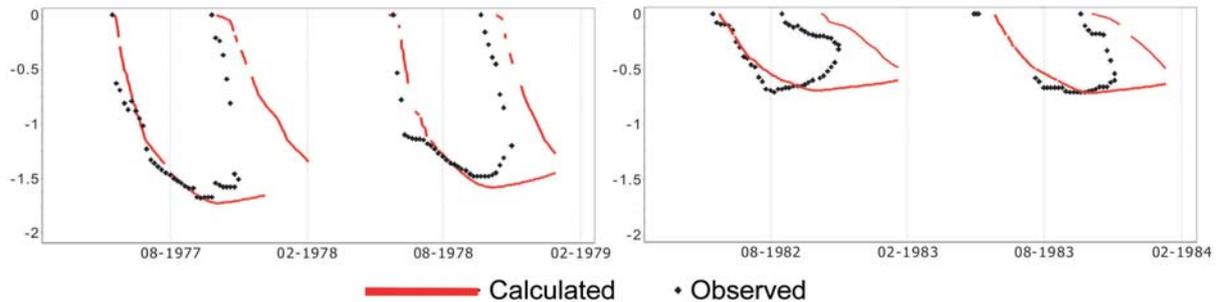

Figure 4. The estimated and observed thawing depth of soil in the stone talus (on the left) and in a swamp forest (on the right).
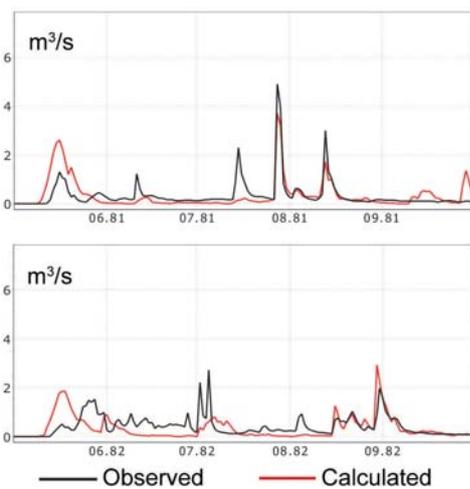

Figure 5. The estimated and the observed runoff hydrographs (m³/s), the Kontaktovy Stream, 1981–1982.

In conclusion, it may be inferred that the model parameters representing hydrophysical properties of frozen soils considerably determine the results of the runoff estimate. Presently we cannot attain satisfactory results in the runoff modeling, despite the fact that they were attained in the modeling of thawing processes. The research requires further development of algorithms of water infiltration into frozen soil of the golets zone.

Conclusions

The goal of this research was to assess the capacity of the "Hydrograph" model to reflect the runoff formation in the permafrost zone. The data of observations over soil thawing were applied to make the parameters more accurate. The particularity of the "Hydrograph" model lies in the fact that physical properties of soil and vegetation cover are used as parameters.

Analysis of the data on the dynamics of the active layer revealed that its thickness depends on the type of soil and vegetation, through which the height, inclination, and aspect of a slope indirectly influence the thawing process. The active layer depth exhibits high variability within the territory of the KWBS, varying from 0.6 m in swamp forests and stream valleys to 1.7 m on bare stone taluses and upper slopes.

The results of the active layer depth modeling showed that such model parameters as soil porosity, maximum water retention capacity of soil, its heat capacity, and thermal conductivity play an important role in the estimate of the heat dynamics in soil. They may be determined based on information on the soil profile and maintain steady values.

The estimated thawing depth of soil in summer coincides with the observed values at both landscapes, while the estimated complete freezing of the active-layer in the cold period occur considerably late in comparison with the observed values. Potentially this problem can be solved by the specification of the algorithm estimating the thermal-insulating influence of snow.

Water discharge in the outlet of the Kontaktovy Stream was modeled with the use of the same values of the model parameters as when estimating the depth of the active layer. The modeling results show that the algorithm block of the model describing the process of water filtration into frozen ground during the snow melting period does not reflect the actual processes adequately enough and requires further development. The results of runoff modeling in the summer period under the condition of a thawed active layer are evaluated as satisfactory.

Model estimates based on long-term detailed observations over the processes in the permafrost zone represent a necessary step toward a reliable parameterization of physically based models. The soil and vegetation parameters corrected and systematized in the process of this research may be applied to evaluate the runoff in the basins with similar natural conditions (Semenova & Lebedeva 2012).

This work shows the importance of observation data for the improvement of the runoff formation models in the permafrost zone. The situation can be considerably improved by reestablishing monitoring at the Kolyma Water Balance Station

Acknowledgments

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