Article

Permafrost hydrology research domain: process-based adjustment

Nikita Tananaev [1,*], Roman Teisserenc [2] and Matvey Debolskiy [3]

[1] Melnikov Permafrost Institute, SB RAS, Yakutsk, Russia; tananaevni@mpi.ysn.ru
[2] EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France; roman.teisserenc@ensat.fr
[2] Geophysical Institute, University of Alaska Fairbanks, Fairbanks AK, USA; mvdebolskiy@alaska.edu
* Correspondence: tananaevni@mpi.ysn.ru;

Abstract: Permafrost hydrology is an emerging discipline, attracting increasing attention as the Arctic region is undergoing rapid change. However, the research domain of this discipline had never been explicitly formulated. Both 'permafrost' and 'hydrology' yield differing meanings across languages and scientific domains, hence 'permafrost hydrology' serves as an example of linguistic relativity. The differing views of permafrost as either an ecosystem class or a geographical region, and hydrology as a discipline concerned with either landscapes or generic water bodies, maintain a language-specific touch in the definition of *permafrost hydrology*. From this point of view, the English and Russian usage of this term is explained. A universal process-based definition is further proposed, developed on a specific process assemblage, including (i) water table dynamics caused by migration of an upper aquitard through freeze–thaw processes; (ii) water migration in soil matrix, driven by phase transitions in the active layer; (iii) transient water storage in solid state in the subsurface compartment. This definition is shown to fill the niche in existing vocabulary, and other definitions from northern hydrology field are revisited.

Keywords: active layer; Arctic hydrology; cold regions hydrology; linguistic relativity; permafrost hydrology

---

1. Introduction

The Arctic is undergoing a sound transformation, affecting climate [1] and ocean temperature [2], sea ice extent [3], terrestrial and marine biodiversity [4-5], driven by the Arctic amplification phenomenon [6-8]. Long–term Arctic change effects on the Arctic water cycle are deduced from observations and reanalysis data [9], while our understanding relies on existing forecasting and modeling experience, together with general assumptions elaborated for temperate regions [10-11]. Whence Arctic terrestrial hydrology is counted similar, coherent or deducible by analogy with temperate regions, its regional uniqueness, or 'Arcticness', may be questioned. However, the Arctic is a frontier ecosystem with distinct features, where permafrost and related effects play an important role.

The hydrological boundaries of the Arctic region are loosely defined by basin approach [12]. The Arctic hydrology domain, as a pan–Arctic drainage area, is hence extended southward up to the smallest headwater streams of the inner Mongolia [13-14]. Integrated across millions of square kilometers of drainage basins, the output signals of natural processes and human impacts are transmitted to the Arctic ocean margin, feeding input to a complex marine system, and impacting global oceanic freshwater turnover and chemistry [15-17]. This integral approach, coined by marine science, blurs the physiographic diversity of the pan–Arctic basin, and a potential diversity of hydrological response throughout the region.

Linking Arctic amplification to Arctic hydrology is complicated by an ambiguity of 'the Arctic' definition, put into hydrological context. One should acknowledge that the Arctic amplification and its effects on terrestrial hydrology occur in a very particular region in the high latitudes, regardless its exact limits. They cannot be understood by analogy with the temperate regions, primarily because of the permafrost–related effects. The latter have an enormous effect on the water cycle, where most hydrological processes are confined to unfrozen layers in an otherwise frozen media [18-20]. The direct linkage between the permafrost thermal state and the heat and water fluxes is a unique regional feature [21-23]. Only in permafrost regions, phase transitions resulting from long-term changes in temperature and/or precipitation definitively affect the hydraulic properties of soils [24].

Permafrost hydrology, as a distinct research field, from its very beginning aimed at better understanding and quantify these interconnections between frozen ground and hydrological processes [25-26]. In a changing Arctic, attention is growing toward the role hydrology plays in the organic matter and nutrient transport [27], and permafrost–climate feedback [28]. Long–term upward trends in the active layer thickness can potentially liberate up to ca. 800 Pg of perennially–frozen highly degradable organic carbon [29-30], the fate and transport of which depend on the hydrological processes in the active layer and in Arctic streams [31-32].

However, the attempts to summarize the current state of knowledge in permafrost hydrology are relatively scarce [11,19,33-34]. A recent review paper by Walvoord & Kurylyk [35] provides a comprehensive overview of the major terms and fundamental concepts of permafrost hydrology. Further advances in permafrost hydrology may require researchers to align their understanding of the discipline domain, research objectives and methods. This brief paper discusses the limits of relevance of permafrost hydrology, as a branch of modern geophysics, in the field of regional and global change research. We attempt to redefine the permafrost hydrology domain through process–based adjustment, and introduce several concepts relevant to future studies in the field.

2. The definition of permafrost hydrology and linguistic relativity

Language is frequently argued to act as an active cognitive tool, both in sciences of humanity and in physics [36]. Science is operating concepts, theories and models, which are all language–based cognitive abstractions. As late A. Einstein [37] put it, "...the mental development of an individual and his way of forming concepts depend to a high degree upon language". Our mode of thought, comprehension and cognition is bound to our native language and its structure, the statement known as the Sapir–Whorf hypothesis [38]. A non–universal nature of the current knowledge originates in part from the international character of science, the development of certain research fields in different language environments. Research in Earth sciences, including both geocryology and hydrology domains, took differing directions in Soviet and Occidental science [39]. Subsequently, in the scientific language of these schools, either the literally identical term is understood differently, or different untranslatable terms do exist. Both cases require a "vocabulary alignment", establishing a common framework for informal discussions and collaboration. In the case of *permafrost hydrology*, both words in the phrase are known to be understood and used differently.

2.1. Permafrost

Permafrost is a layer of soil, rock, sediment or other earth material with a temperature that has remained negative for two or more consecutive years, irrespective of its lithology or water/ice content [40]. This definition remains unchanged, virtually unchallenged and is widely used in Occidental literature [41]. Put simple, it allows the researchers to conclude on the presence at a given point (*e.g.* pit, borehole) and, by extension, at a given depth, of frozen material that represents, and embodies, permafrost. This definition assigns a term to a specific thermal state of soil or rock parcel rather to an object or event class *per se* [42], and by extension, to a certain geological stratum, a three–dimensional volume of frozen material. It yields certain material and temporal aspects, but otherwise is largely void of context, and has to be placed in such to be properly understood. As such, it makes part of several constructions, denoting:

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 May 2019 doi:10.20944/preprints201905.0154.v1

(a) *generic properties*: permafrost + (thermal state); the only example since permafrost is defined uniquely through temperature;

(b) *physical properties*: permafrost + (temperature, ice content); otherwise, 'frozen soil' is used in references to particular material properties, such as heat transmissivity, hydraulic conductivity, unfrozen water content *etc*;

(c) *spatial aspect*: permafrost + (region, area, zone, extent, distribution), also 'permafrost type'; (subsea, mountain, lowland, continuous, isolated) + permafrost, addressing physiographical settings, and continuity;

(d) *geological features*: permafrost + (base, table, thickness);

(e) *temporal evolution*: permafrost + (dynamics, development, degradation/aggradation, thawing/melting), though never 'permafrost freezing';

(f) *relative or possessive case*: permafrost + (construction, foundation, map, model, soil, carbon pool, loss).

Russian scientific language discerns different aspects of permafrost, by assigning different terms to permafrost:

(a) as a phenomenon: *мерзлота* [mʲɪrzlɐtˈa], frozen ground, or rather *многолетне-мерзлые породы* [mnəɡɐlʲˈetnʲɪ-mʲˈɵrzlɨjə pɐrˈodɨ], perennially frozen rock;

(b) as a territory underlain by those, fully or partially: *криолитозона*, [krˈiolʲitɐzˈonə], permafrost zone;

(c) a three–dimensional geological body: *многолетне-мерзлая толща* [mnəɡɐlʲˈetnʲɪ-mʲˈɵrzlɐj tˈolɕɕɐ], perennially frozen rock layer).

Here *kryolitozona* connotes a specific physiographic region, whereas *mnogoletne–merzlaya tolscha* emphasizes the vertical dimension of a frozen layer, though the two definitions are often used interchangeably in the Russian literature.

2.2. Hydrology

The comparable level of ambiguity exists in defining 'hydrology' across languages. In the English usage, *hydrology* refers mainly to a research discipline preoccupied with water, but can also be used to reference the totality of water–related processes, and/or water budget of a particular water body. The most frequent use includes constructions referring to:

(a) *methods and applications*: (statistical, isotope, engineering, computational, contaminant) + hydrology, these are all separate research disciplines;

(b) *water cycle elements*: (surface–water, groundwater) + hydrology;

(c) *compartments*: (surface, subsurface, soil, active layer) + hydrology;

(d) *landscapes and specific objects*: (prairie, forest, peatland, floodplain, glacier, subglacial, periglacial) + hydrology, implies the specific water cycling processes in these ecosystems; though extremely rarely 'tundra hydrology', and never 'lake/river hydrology';

(e) *spatial aspect*: (land, catchment, watershed, drainage basin) + hydrology;

(f) *frozen water*: (snow, ice, meltwater) + hydrology; though never 'rain hydrology';

(g) *particular water bodies*: hydrology of the + (Pacific Ocean, Lena River, Great Lakes; each water body can have its proper hydrology;

(h) *particular regions*: hydrology of the + (Everglades, Polk County, Northern Carolina, Arctic).

In Russian scientific vocabulary, this term has coherent meaning, but distinctly different usage. The prevalent use is oriented towards generic objects void of spatial context, hence river/lake/reservoir/wetland hydrology' are all legitimate terms for disciplines studying these water bodies *per se*. Landscapes, as connoting landcover classes, are never covered by the term, thus 'forest hydrology' is absent from Russian vocabulary. Methods and applications form disciplines' names in virtually the same style, *e.g.* 'engineering hydrology'. Likewise, distinct water objects can have its own hydrology, *e.g.* 'the Danube Delta hydrology', but not the regions, thus 'Arctic hydrology' is an illegitimate term. However, 'Arctic Ocean drainage basin hydrology' may serve as a close substitute, coherent to the modern vision [11], and underscoring the fact that there is much less of the Arctic in our 'Arctic hydrology' speech than we would normally assume.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 May 2019 doi:10.20944/preprints201905.0154.v1

2.3. Permafrost hydrology

Perennially and seasonally thawed layers, such as taliks and notably the active layer, are excluded from permafrost by definition. However, it is frequently stated that 'most biogeochemical and hydrological processes in permafrost are confined to the active layer' [43]. The active layer is inherent to permafrost, as are the taliks, neither making part of it however. These are all layers, <u>void of permafrost</u> by definition. Whatever is occurring in these layers, occurs outside permafrost. Hydrological processes are nevertheless only active in these non-frozen media; that said, do they really take place **in** permafrost?

Preceding discussion answers this question. Permafrost can be defined as either a geological stratum, an ecosystem class, or a region; and meanings could be switched 'on the fly', as shows the paragraph above. The other point is that *permafrost hydrology* may refer to a research discipline (the scope of this paper), or a totality of terrain–specific hydrological processes. This ambiguity is language–specific, since it exists in English but is impossible in Russian, where no hydrology of ecosystem classes is possible, and hydrology is a discipline name, just occasionally applied to particular water bodies.

In Occidental literature, permafrost hydrology is a research discipline, studying "...the direct and indirect effects of perennially frozen ground on the properties, occurrence, distribution, movement and storage of water" [25]. This definition is an elegant attempt to express what comes evident from our reasoning, that permafrost hydrology is studying hydrology in permafrost. As such, it mimics the constructions like *forest hydrology*, and maintains a notion to permafrost as a specific landcover (or 'undercover') or ecosystem class, therefore no Russian analogue could exist (see above). Since permafrost is frozen soil/rock, the term interestingly aligns with the use of 'hydrology' with other frozen substrates, snow and ice.

In Russian usage, this discipline name took form 'permafrost rivers hydrology', or *гидрология рек криолитозоны* [gɪdr ɐlˈ ogɪjə rʲˈek krˈiolʲitɐzˈonɨ], in a late 1980s Russian text by B.L. Sokolov, later published in English as 'Hydrology of rivers of the cryolithic zone in the U.S.S.R.' [44]. Eventually, '*gidrologiya kriolitozony*' (permafrost hydrology) was used, though infrequently, in Russian literature, and a permafrost hydrology laboratory was active at State Hydrological Institute (Saint–Petersburg) since early 1990s until 2007.

How can we define whether a specific hydrological process has anything to do with permafrost hydrology? Hydrological objects vary greatly in size, and the largest Arctic drainage basins can have their headwaters either in discontinuous permafrost regions, or non-permafrost areas. Which share should permafrost hydrology claim in these cases, and how may we discern it from other hydrologies?

3. Permafrost hydrology: process-based definition

In permafrost domain, water finds its way from precipitation, snowmelt or ground ice meltdown to streams, subjected to the universal action of gravity, much as elsewhere on Earth. Viewed as a region, permafrost (*kriolitozona*) hosts processes, unrelated to the frozen ground influence on water transfer and storage. Universal physical laws are governing water movement at any given point, but a specific set, or 'assemblage', of hydrological processes may exist, defining which laws are the most applicable, and which forces are dominating, under particular conditions and in particular landscapes. This approach is not uncommon to Earth sciences. Geomorphology acknowledges specific landforms as imprints of particular (set of) geomorphic processes or events, *e.g.* palaeo-ice stream beds [45], and defines the environment through landform assemblages, notably the definition of paraglacial environment [46].

Permafrost can be perceived, by definition, as a specific ecosystem class, thence, arguably, there exists a typical assemblage of hydrological processes, through which a research domain of permafrost hydrology can be defined. The unique process assemblage for permafrost hydrology includes: (a) water table migration caused by upper aquitard development through freeze–thaw processes; (b) water migration in soil matrix, driven by phase transitions in the active layer; (c) transient water storage in solid state in the subsurface compartment. Implied processes are not

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 May 2019 doi:10.20944/preprints201905.0154.v1

solely hydrological, and may also be regarded as cryogenic, related to phase transitions in soils [47], or periglacial, driving landscape conditioning by frost action [48].

3.1. Water table migration

Thawing front, or the active layer base, acts as a cryogenic aquitard for the percolating water [49]. Infiltration is restricted by frozen soil or, under certain conditions in frost heave–susceptible soils, by segregation ice lenses formed during freezing [50]. Hydraulic conductivity of frozen soils depends on the volume of pores occupied by ice: it varies from 15% to 35% of the non-frozen soil when ice content is between 0.3 and 0.5, and declines to almost zero at ice content over 0.6 [51]. Rapid decline in hydraulic conductivity is in part related to selective freezing of soil pores, when larger pores freeze earlier owing to lower capillary forces [52].

Thawing front position within the soil column evolves through a temporal continuum of states, as shown in Figure 1, and hydrological processes follow this evolution [18,35,53]. The annual cycle starts in late winter when the active layer is frozen and the subsurface compartment is virtually void of moving water. Solar radiation penetrates the snow cover [54], and early thawing in topsoil can proceed under snow. Subsequently, this thawed layer partly accommodates meltwater runoff during spring.

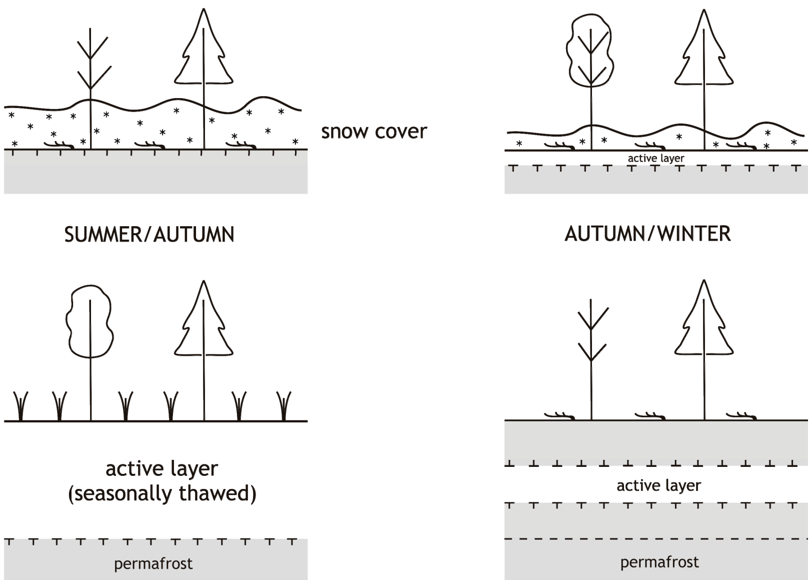

Figure 1. Active layer is a dynamic feature, whose state is constantly evolving. Snapshots of typical and illustrative states are shown, though intermediate states do exist and form a temporal continuum.

Seasonal thaw develops throughout warm period, and groundwater table variations during this time can be caused solely by the thawing front propagation. On the onset of autumn, when soil starts refreezing, the active layer *de facto* accommodates two aquitards, (a) frozen top–soil surface, (b) active layer base, which is also a local freezing front. The former limits late autumn rainwater infiltration, while the latter accumulates available water to form an ice–rich transient layer [55]. The unfrozen soil stores water throughout freezing period, and may reroute it toward the streams late winter or early spring [56].

Permafrost virtually eliminates loss to infiltration and cuts off deep ground water recharge, except by talik zones. Catchment response to storms therefore depends less on antecedent conditions, and active layer depth is an important factor. Active layer development leads to decreasing water table slope and hydraulic head in the subsurface compartment, affecting stream–groundwater interaction.

3.2. Soil water migration

Water redistribution in the active layer occurs mostly during active layer freezing, and affects both vertical and lateral migration. Vertical water migration to the freezing front is observed in fine–grained soils [57] and peat [58], while in coarser material, water is forced to migrate downward from the freezing front [59]. Pore pressure excess in the residual active layer during late autumn and early winter (Figure 1) promotes lateral migration of water in the saturated layer, what is called 'piston flow' in Russian literature [59].

Ice lenses developed in soil through ice segregation serve as local freezing fronts, hence several regions of upward and/or downward migration can be present in the active layer at any given moment. Consequently, multiple local desiccation zones are developed in the soil profile, causing differential compaction, cracking, and resulting in an overall increase in vertical permeability [60] and hydraulic conductivity [61].

3.3. Transient water storage

Permafrost is capable of redistributing water fluxes, acting in a wide range of timescales. Seasonally, water can be captured in the active layer as textural and segregation ice in winter, to be released in spring and summer upon active layer thawing. In clastic material, *e.g.* blockfields or kurums, spring meltwater freeze up in large pores and is released as summer advances [62]. Icings are typical permafrost hydrology features, that can capture, store and redistribute groundwater on the timescale from seasons to several years or even decades [44,63-64]. The runoff volume intercepted by icings can be as high as 12% to 22% of total basin discharge under continuous permafrost conditions [65]. Water trapped in ice-rich transient layer will only be released upon continuous climate warming, which is on timescales from hundreds to thousand years [55]. Ice wedges and textural or massive ice, e.g. in the Ice Complex deposits or buried glaciers, can be preserved throughout millennia before re-entering the global water cycle when exposed in river banks or marine cliffs or subject to thermokarst degradation [66-67].

Hydrological and cryological processes occurring within the "permafrost area" explain the diversity and complexity of "permafrost hydrology". Accordingly, its definition should not be static, and should integrate this complexity, in terms of both spatial variability and temporal evolution.

4. Permafrost hydrology: spatial domain

Hydrological studies are generally based on basin approach. An elementary watershed is the smallest response unit, and water routing processes are spread and averaged across. Though some processes are studied at a stand scale, *e.g.* infiltration or transpiration, observed river runoff is attributed to a certain catchment area, where water routing and transfer do occur.

Plethora of studies concerning permafrost hydrology and defining its current state were conducted in discontinuous and even sporadic permafrost regions, wherever permafrost underlies the full areal extent of the research site [68]. An effective budget-saving strategy, this approach requires a certain degree of coalescence between the permafrost extent and the study area extent, to be relevant as a permafrost hydrology study.

To formally define if a study can be distinguished as permafrost hydrology study, we suggest a strategy described further in the Table 1. The applicability of this strategy depends on relative scale of the study compared to extent of global permafrost regions defined by continuity criteria [69]. For the small-scale studies, at least the active layer and top of the permafrost should be included in the domain, so that all the processes associated with active layer could be accounted for. The mesoscale (ca. 25 – 2 500 km^2) catchments are included in the permafrost hydrology domain when their surface is underlain by continuous permafrost. In discontinuous permafrost, the existing taliks under lakes and channels are to be closed or, if these are open taliks, they should play a significant confining role for the sub-permafrost aquifer [72]. On the global basin scale, the presence of permafrost-affected

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 May 2019 doi:10.20944/preprints201905.0154.v1

sub-catchments should be acknowledged, and relevant cryogenic processes should be taken into account.

Table 1 Permafrost hydrology applicability in relation to both permafrost and study extent

Study area extent	Area	Permafrost extent			
		patchy < 10%	sporadic 10-50%	discontinuous 51-90%	continuous > 90%
Stand plot	point	Yes	Yes	Yes	Yes
Slope; representative elementary watershed, REW [70]	< 10 km²	No	Yes	Yes	Yes
Mesoscale watershed; hydrological response unit, HRU [71]	< 2 500 km²	No	No	Yes	Yes
Macroscale watershed and global basins	> 2 500 km²	Permafrost-affected HRUs should be explicitly described or modelled as such			

5. Definitions in Arctic hydrology: existing and revised

5.1. Existing definitions

Research fields emerging from acknowledgement of a highly regional character of hydrological processes include: Arctic hydrology, cold–regions hydrology, high–latitude hydrology, northern hydrology, periglacial hydrology, permafrost hydrology, polar hydrology. These terms are used interchangeably, without giving a notice, and the difference is largely unclear and confusing.

Arctic hydrology is widely used to denote the processes in the Arctic Ocean and atmosphere, where terrestrial sub–system plays a minor role [14]. Recently, *Arctic terrestrial hydrology* was thoroughly reviewed, its terrestrial contributing area expanded well beyond Arctic river basins, while Arctic freshwater domain embraces the good part of the Northern Hemisphere, including atmospheric and marine compartments [10].

The 40°N latitude roughly serves as a southern limit for the *cold–regions hydrology*, though other specific criteria are imposed on the definition of a cold region [19]. *High–latitude hydrology*, in its turn, envisions its southern limit at 60°N latitude [47], sharing it with *northern hydrology* in its earlier definition [73]. Later, *northern hydrology* has been encompassing the processes in the tundra and taiga ecosystems [74], or post–glacial settings in boreal, temperate coniferous and mixed forests [75].

Periglacial hydrology was used once to address the processes in the periglacial sector of Vatnajökull ice cap [76]. Since permafrost is in the heart of periglacial landscapes, *permafrost hydrology* may stand for periglacial hydrology in the hydrologist’s eyes. *Polar hydrology* was a recent research effort of Norwegian Water Resources and Energy Directorate in Svalbard [77].

5.2. Revised definitions

The Arctic region is part of the global system, and as such receives influence from many distant regions, that should not be added to the Arctic domain on this purpose. True, that Arctic boundary has several definitions, both political and natural, and what is included, depends on the scope. However, the only boundary which has been clearly demarcated is a political boundary, and the view of the Arctic as a political region, and not an ecoregion, is arguably more correct. In this case, *Arctic hydrology* should focus on freshwater resources in the Arctic regions, its quantification, availability and quality, and hydrological risk assessment, serving the people of the North. 'Acknowledge, not include' is a proper strategy for defining domains, including that of Arctic hydrology.

Ecosystem, or ecoregion boundaries are used to define northern, or boreal, hydrology as concerned with tundra and taiga ecosystems, and interactions between vegetation communities and water fluxes [74]. 'Northern' requires a supplementary definition of 'southern hydrology', be it either Antarctic or Mediterranean climate. Hence, *boreal hydrology* sounds more appropriate, as connoting the existence of typical boreal ecosystems, such as forests (*taiga*) and wetlands.

High–latitude hydrology, as a definition, is subject to a question of which latitude is high enough, in hydrological sense. High latitudes are felt 'high' thanks to rough climate, therefore high–latitude is defined here as hydrology of Köppen *E* climate regions, including any regional study concerning particular rivers or watersheds, and emphasizing particular site–specific features, as highly seasonal flow, snow redistribution impact *etc*. As such, it makes part of larger *cold–regions hydrology* domain, where cold regions are defined based on climate [14]. With progressive climate change, warming the Arctic at an impressive rate, these definitions will also change their spatial coverage.

Climate boundaries of Köppen classification will shift southward, and regions previously considered as cold are expected to become warmer. High-latitude and cold-region hydrology could be therefore considered as endangered species. We should track vigilantly the hydrological effects of these changes; this is, to our opinion, one of the most important objectives of permafrost hydrology research.

6. Future progress in permafrost hydrology domain

Permafrost hydrology is already a well-established research discipline as well as a general framework for the scientific advance and planning, even though the use of the term is undermined by a strong blend with other terminologies. Upon defining its scope and objectives, its major concern should turn to the development of discipline–specific methods, best suited for particular research purposes.

Tracer hydrology methods are promising in acquiring information on flow paths and residence times in northern catchments [75,78]. Freeze–thaw processes leave a distinct imprint on ^{2}H and ^{18}O signatures in soil moisture, that can be traced to specific locations (by soil type), processes (*e.g.* ice segregation), ground ice forms (pingo, aufeis, ice wedges), or, speculatively, even to certain cryostructures. Rare earth elements are used to track hydrologic pathways, distinguishing fast and slow subsurface flows, or mineral or organic layers [79]. These data should be used in combination with field data on active layer dynamics, water table, vegetation, and precipitation, including rain chemistry, in assessing the activity of certain flowpaths and its spatio–temporal variability.

Organic carbon and its transformation affected by hydrological processes, is a subject of utter importance in the scope of permafrost–climate feedback. Methane production is an anaerobic process, depending on the permafrost thaw rate and the water table position in the soil profile ([80], and references therein). Old permafrost–derived carbon is highly biodegradable, and is rapidly consumed by bacteria in headwater system [81-82]. Optical and molecular properties of dissolved organic carbon can be used to track the reaction of slopes and headwaters to progressive active layer development.

Modelling strategies accounting for permafrost-specific processes should be developed or further enhanced for their better representation. The most promising approaches include: (i) coupled water and heat balance models of various dimension and complexity, e.g. 'zero-dimensional' model of Boike et al. [22], PFLOTRAN [83], SUTRA 3.0 (aka SUTRA-ice) [84] and permaFOAM [85], to mention but a few; (ii) explicit two-dimensional heat transfer model with phase transitions, where water and heat fluxes are decoupled [86]; (iii) semi-distributed models with simplistic permafrost description as an impermeable layer, and no heat transfer module [87-88].

Water movement and redistribution in the subsoil compartment, along with phase transitions and related volumetric changes, necessarily perform geomorphic work. This complex overlap gives birth to a certain cryo–fluvial interaction [89], where periglacial landforms develop as a function of local hydrology, while surface runoff reuses and reshapes linear forms created by cryogenic processes. Ultimately, integrated models should be developed describing the water routing in the subsoil, its heat imprint and geomorphic consequences, the development of non-channelized drainage network (water tracks) and thermokarst gullies.

7. Conclusions

Hydrological processes in periglacial environments are often regarded as "…azonal processes operating in cold environments", and as such believed to "…differ little, if at all, from similar processes in other climatic environments" [48]. They are thought to be "...not unique to [permafrost] districts, but their intensities differ from those in temperate latitudes [25]. From what is known, the conclusion is that permafrost hydrology can be defined through a process assemblage, unique for permafrost regions. Other hydrologies do exist, and, having their definitions and scopes revised, could provide extremely important insights. This paper offers such revision, and other revisions may follow, to the benefit for conscious science, and the Northern communities.

Scientific advance is constrained by the absence of common language, untranslatability of major 'local' terms coined by different national schools. This constraint can only be overruled by the acknowledging the existence of multiple meanings in national scientific domains, and cross-linking these meanings, by discussion and consensus. Advancement of research and collaboration is sustained by this terminological framework, elaborated by the researchers in order to transfer and share their expertise. Clear research objectives and hypotheses arguably serve science not less than our sophisticated field and modeling methods.

Author Contributions: All authors contributed to the text. Conceptualization and writing – original draft preparation, N.T.; writing – review and editing, N.T, R.T. and M.D. All authors have approved the submitted version of the manuscript.

Funding: This research was partially funded by Russian Fund for Basic Research, project №17-05-00948a (N.T.), TOMCAR-Permafrost Marie Curie International Reintegration Grant FP7-PEOPLE-2010-RG, project reference: 277059 (R.T.).

Acknowledgments: The paper was conceived and partially written while N.T. served as an invited professor to EcoLab, Université de Toulouse, CNRS, INPT, UPS, Toulouse, France. The support and assistance from EcoLab staff are highly appreciated.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

References

1. Sorokina, S.A.; Li, C.; Wettstein, J.J.; Kvamstø, N.G. Observed atmospheric coupling between Barents Sea ice and the warm–Arctic cold–Siberian anomaly pattern. *J Clim.* **2016**, *29*, 495–511. DOI: 10.1175/JCLI–D–15–0046.1.
2. Wijffels, S.; Roemmich, D.; Monselesan, D.; Church, J.; Gilson, J. Ocean temperatures chronicle the ongoing warming of Earth. *Nat Clim Change* **2016**, *6*, 116–118. DOI: 10.1038/nclimate2924.
3. Francis, J.A.; Chan, W.; Leathers, D.J.; Miller, J.R.; Veron, D.E. Winter Northern Hemisphere weather patterns remember summer Arctic sea–ice extent. *Geophys Res Lett.* **2009**, *36*, L07503. DOI: 10.1029/2009GL037274.
4. Sturm, M.; Racine, C.; Tape, K. Increasing shrub abundance in the Arctic. *Nature* **2001**, *411*, 546–547.
5. Cronin, T.M.; Cronin, M.A. Biological response to climate change in the Arctic Ocean: the view from the past. *Arctos* **2015**, *1(4)*. DOI: 10.1007/s41063-015-0019-3.
6. Holland, M.M.; Bitz, C.M. Polar amplification of climate change in coupled models. *Clim Dyn.* **2003**, *21*, 221–232. DOI: 10.1007/s00382-003-0332-6.
7. Serreze, M.C.; Barrett, A.P.; Stroeve, J.C.; Kindig, D.M.; Holland, M.M. The emergence of surface-based Arctic amplification. *The Cryosphere* **2009**, *3*, 11–19. DOI: 10.5194/tc-3-11-2009.
8. Serreze, M.C.; Barry, R.G. Processes and impacts of Arctic amplification: A research synthesis. *Glob Planet Change* **2011**, *77*, 85–96. DOI: 10.1016/j.gloplacha.2011.03.004.

9. Serreze, M.C.; Bromwich, D.H.; Clark, M.P.; Etringer, A.J.; Zhang, T.; Lammers, R. Large-scale hydro-climatology of the terrestrial Arctic drainage system. *J Geophys Res.* **2002**, *108*, D2, 8160. DOI: 10.1029/2001JD000919.
10. Francis, J.A.; White, D.M.; Cassano, J.J.; Gutowski Jr, W.J.; Hinzman, L.D.; Holland, M.M.; Steele, M.A.; Vörösmarty, C. An arctic hydrological system in transition: Feedbacks and impacts on terrestrial, marine and human life. *J Geophys Res.* **2009**, *114*, G04019. DOI: 10.1029/2008JG000902.
11. Bring, A.; Fedorova, I.; Dibike, Y.; Hinzman, L.; Mård, J.; Mernild, S.H.; Prowse, T.; Semenova, O.; Stuefer, S.L.; Woo, M.K. Arctic terrestrial hydrology: A synthesis of processes, regional effects, and research challenges. *J Geophys Res: Biogeosci.* **2016**, *121*, 621–649. DOI: 10.1002/2015JG003131.
12. Lammers, R.B.; Shiklomanov, A.I.; Vörösmarty, C.; Fekete, B.M.; Peterson, B.J. Assessment of contemporary Arctic river runoff based on observational discharge records. *J Geophys Res.* **2001**, *106*, 3321–3334.
13. Syed, T.H.; Famiglietti, J.S.; Zlotnicki, V.; Rodell, M. Contemporary estimates of Pan–Arctic freshwater discharge from GRACE and reanalysis. *Geophys Res Lett.* **2007**, *34*, L19404. DOI: 10.1029/2007GL031254.
14. Prowse, T.; Bring, A.; Mård, J.; Carmack, E.; Holland, M.; Instanes, A.; Vihma, T.; Wrona, F.J. Arctic Freshwater Synthesis: Summary of key emerging issues. *J Geophys Res: Biogeosci.* **2015**, *120*, 1887–1893. DOI: 10.1002/2015JG003128.
15. Fichot, C.G.; Kaiser, K.; Hooker, S.B.; Amon, R.M.W.; Babin, M.; Bélanger, S.; Walker, S.A.; Benner, R. Pan-Arctic distributions of continental runoff in the Arctic Ocean. *Scientific Rep.* **2013**, *3*, 1053. DOI: 10.1038/srep01053.
16. Nummelin, A.; Illcak, M.; Li, C.; Smedsrud, L.H. Consequences of future increased Arctic runoff on Arctic ocean stratification, circulation, and sea ice cover. *J Geophys Res: Oceans* **2016**, *121*, 617–637. DOI: 10.1029/2015JC011156.
17. Semiletov, I.; Pipko, I.; Gustaffson, Ö.; Anderson, L.G..; Sergienko, V.; Pugach, S.; Dudarev, O.; Charkin, A.; Gukov, A.; Bröder, L.; Andersson, A.; Spivak, E.; Shakhova, N. Acidification of East Siberian Arctic Shelf waters through addition of freshwater and terrestrial carbon. *Nat Geosci.* **2016**, 9, 361–365. DOI: 10.1038/ngeo2695.
18. Hinzman, L.; Kane, D.L.; Gieck, R.E.; Everett, K.R. Hydrologic and thermal properties of the active layer in the Alaskan Arctic. *Cold Reg Sci Technol.* **1991**, *19(2)*, 95–110.
19. Woo, M.K. *Permafrost hydrology*. Springer: Berlin Heidelberg, Germany, 2012; 564 p.
20. Kane, D.L.; Yoshikawa, K.; McNamara, J.P. Regional groundwater flow in an area mapped as continuous permafrost, NE Alaska (USA). *Hydrogeol J.* **2013**, *21*, 41–52.
21. Wright, R.K. Preliminary results of a study on active layer hydrology in the discontinuous zone at Schefferville, Nouveau–Québec. *Géographie physique et Quaternaire* **1979**, *33*, 359–368. DOI: 10.7202/1000370ar.
22. Boike, J.; Roth, K.; Overduin, P.P. Thermal and hydrologic dynamics of the active layer at a continuous permafrost site (Taymyr Peninsula, Siberia). *Water Resour Res.* **1998**, *34*, 355–363. DOI: 10.1029/97WR03498.
23. Weismüller, J.; Wollschläger, U.; Boike, J.; Pan, X.; Yu, Q.; Roth, K. Modeling the thermal dynamics of the active layer at two contrasting permafrost sites on Svalbard and on the Tibetan Plateau. *The Cryosphere* **2011**, *5*, 741–757. DOI: 10.5194/tc-5-741-2011.
24. Burt, T.P.; Williams, P.J. Hydraulic conductivity in frozen soil. *Earth Surf Proc*. **1976**, *1*, 349–360.
25. Woo, M.K. Permafrost hydrology in North America. *Atmosphere-Ocean* **1986**, *24*, 201–234.
26. Woo, M.K.; Kane, D.L.; Carey, S.K.; Yang, D. Progress in permafrost hydrology in the new millennium. *Permafr Periglac Process.* **2008**, *19*, 237–254. DOI: 10.1002/ppp.613.
27. Frey, K.E.; McClelland, J.W. Impacts of permafrost degradation on arctic river biogeochemistry. *Hydrol Process.* **2009**, *23*, 169–182.
28. Lawrence, D.M.; Koven, C.D.; Swenson, S.C.; Riley, W.J.; Slater, A.G. Permafrost thaw and resulting soil moisture changes regulate projected high-latitude CO_2 and CH_4 emissions. *Environ Res Lett.* **2015**, *10(9)*, 094011. DOI: 10.1088/1748-9326/10/9/094011.
29. Abbott, B.W.; Larouche, J.R.; Jones, J.B.; Bowden, W.B.; Balser, A.W. Elevated dissolved organic carbon biodegradability from thawing and collapsing permafrost. *J Geophys Res: Biogeosci.* **2014**, *119*, 2049–2063. DOI: 10.1002/2014JG002678.
30. Hugelius, G.; Strauss, J.; Zubrzycki, S.; Harden, J.W.; Schuur, E.A.G.; Ping, C.-L.; Schirrmeister, L.; Grosse, G.; Michaelson, G.J.; Koven, C.D.; O'Donnell, J.A.; Elberling; B.; Mishra, U.; Camill P.; Yu, Z.;

Palmtag, J.; Kuhry, P. Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosci.* **2014**, *11*, 6573–6593. DOI: 10.5194/bg-11-6573-2014.

31. Cory, R.M.; Ward, C.P.; Crumb, B.C.; Kling, G.W. Sunlight controls water column processing of carbon in arctic fresh waters. *Science.* **2014**, *345(6199)*, 925–928. DOI: 10.1126/science.1253119.
32. Lessels, J.S.; Tetzlaff, D.; Carey, S.K.; Smith, P.; Soulsby, C. A coupled hydrology–biogeochemistry model to simulate dissolved organic carbon exports from a permafrost–influenced catchment. *Hydrol Process.* **2015**, *29*, 5383–5396. DOI: 10.1002/hyp.10566.
33. Woo, M.-K.; Marsh, P.; Pomeroy, J.W. Snow, frozen soils and permafrost hydrology in Canada, 1995-1998. *Hydrol Process.* **2000**, *14*, 1591–1611.
34. Hinzman, L.D.; Kane, D.L.; Woo, M.-K. Permafrost Hydrology. In *Encyclopedia of Hydrological Sciences*; Anderson, M., Ed. Wiley: West Sussex, U.K., 2005; Volume 4, pp. 2679–2693.
35. Walvoord, M.A.; Kurylyk, B.L. Hydrologic impacts of thawing permafrost – A review. *Vadose Zone J.* **2016**, *15(6)*. DOI: 10.2136/vzj2016.01.0010.
36. Ford, A.; Peat, F.D. The role of language in science. *Foundations of Physics* **1988**, *18(12)*, 1233–1242. DOI: 10.1007/BF01889434.
37. Einstein, A. The common language of science. *Out of my later years*, 1941; 111–113.
38. Whorf, B.L. Science and linguistics. *Technology Review* **1940**, *42(6)*, 229–231, 247–248.
39. French, H. The development of periglacial geomorphology: 1 – up to 1965. *Permafr Periglac Process.* **2003**, *14*, 29–60. DOI: 10.1002/ppp.438.
40. Müller, S.W. Permafrost of perennially frozen ground and related engineering problems, *U.S.Geological Survey Special Report, Strategic Engineering Study 62*. Washinton, D.C., U.S. Government Printing Office; 1945.
41. Romanovsky, V.; Smith, S.E.; Christiansen, H.H. Permafrost thermal state in the polar Northern Hemisphere during the International Polar Year 2007-2009: a synthesis. *Permafr Periglac Process.* **2010**, *21(2)*, 106–116. DOI: 10.1002/ppp.689.
42. Dobiński, W. Permafrost. *Earth–Science Reviews* **2011**, *108*, 158–169. DOI: 10.1016/j.earscirev.2011.06.007.
43. ACIA. *Arctic Climate Impact Assessment*. Symon C, Arris L, Heal B. (eds), Cambridge: Cambridge University Press; 2005.
44. Sokolov, B.L. Hydrology of rivers of the cryolithic zone in the U.S.S.R. *Nordic Hydrol.* **1991**, *22(4)*, 211–226.
45. Ottesen, D.; Stokes, C.R.; Bøe, R.; Rise, L.; Longwa, O.; Thorsnes, T.; Olesen, O.; Bugge, T.; Lepland, A.; Hestvik, O.B. Landform assemblages and sedimentary processes along the Norwegian Channel Ice Stream. *Sediment Geol*. **2016**, *338*, 115–137. DOI: 10.1016/j.sedgeo.2016.01.024.
46. Slaymaker, O. Criteria to discriminate between proglacial and paraglacial environments. *Landf Analys.* **2007**, *5*, 72-74.
47. Bartsch, A. Monitoring of terrestrial hydrology at high latitudes with scatterometer data. In *Geoscience and remote sensing: New achievements*; Imperatore, P., Riccio, D., Eds.; Intech: 2010, pp. 247-262.
48. French, H.; Thorne, C.E. The changing nature of periglacial geomorphology. *Géomorphologie: relief, processus, environnement* **2006**, *3*, 165–174. DOI: 10.4000/geomorphologie.119.
49. Fotiev, S.M. Underground waters of cryogenic area of Russia. *Earth Cryosphere* **2013**, *XVII(2)*, 41–59 [in Russian, with English abstract].
50. Konrad, J.M.; Duquennoi, C. A model for water transport and ice lensing in freezing soils. *Water Resour Res.* **1993**, *29(9)*, 3109–3124.
51. Boytsov A.V. *Usloviya formirovaniya i rezhim podzemnykh vod nadmerzlotnogo i mezhmerzlotnogo stoka v Tsentral'noy Yakutii* (Formation conditions and groundwater regime of supra-permafrost and permafrost runoff in Central Yakutia). PhD Thesis, P.I. Melnikov Permafrost Institute, Yakutsk. 2002 (in Russian).
52. Fel'dman G.M. *Peredvizheniye vlagi v talykh i promerzayushchikh gruntakh* (Water migration in thawed and freezing soils). Nauka: Novosibirsk, U.S.S.R., 1988 (in Russian).
53. Quinton, W.L.; Shirazi, T.; Carey, S.K.; Pomeroy, J.W. Soil ware storage and active layer development in a sub–alpine tundra hillslope, Southern Yukon Territory, Canada. *Permafr Periglac Process*. **2005**, *16*, 369–382. DOI: 10.1002/ppp.543.
54. O'Neill, A.D.J.; Gray, D.M. Solar radiation penetration through snow. In *IAHS Publ. 107*, 1973, pp. 227–241.
55. Shur, Yu.; Hinkel, K.M.; Nelson, F.E. The transient layer: Implications for geocryology and climate–change science. *Permafr Periglac Process.* **2005**, *16*, 5–17. DOI: 10.1002/ppp.518.

56. Streletsky, D.; Tananaev, N.; Opel, T.; Shiklomanov, N.I.; Nyland, K.E.; Streletskaya, I.D.; Tokarev, I.; Shiklomanov, A.I. Permafrost hydrology in changing climatic conditions: seasonal variability of stable isotope composition in rivers in discontinuous permafrost. *Environ Res Lett.* **2015**, *10*, 095003. DOI: 10.1088/1748-9326/10/9/095003.
57. Iwata, K. Driving force for water migration in frozen clayey soil. *Soil Sci Plant Nutrition* **1980**, *26(2)*, 215–227. DOI: 10.1080/00380768.1980.10431205.
58. Nagare, R.M.; Schincariol, R.A.; Quinton, W.L.; Hayashi, M. Effects of freezing on soil temperature, freezing front propagation and moisture redistribution in peat: laboratory investigations. *Hydrol Earth Syst Sci.* **2012**, *16*, 501–515. DOI: 10.5194/hess-16-501-2012.
59. Kalyuzhny, I.L.; Lavrov, S.A. *Hydrophysical processes in drainage basins: experimental studies and modeling*; Nestor–Istoriya: St. Petersburg, Russia, 2012.
60. Chamberlain, E.J.; Gow, A.J. Effect of freezing and thawing on the permeability and structure of soils. *Eng Geol.* **1979**, *13*, 73–92.
61. Sterpi, D. Effect of freeze–thaw cycles on the hydraulic conductivity of a compacted clayey silt and influence of the compaction energy. *Soils Found.* **2015**, *55(5)*, 1326–1332. DOI: 10.1016/j.sandf.2015.09.030.
62. Bantzekina, T.V. Ice content variations in coarse talus during spring snow melting. *Kolyma* **2001**, *2*, 28–31.
63. Sokolov, B.L. Certain features in structure and mechanical break-down of naleds, their significance in estimates of naled runoff. In *Siberian Naleds*; Alekseev, V.R., Ed.; U.S. Army CRREL: Hanover, N.H., U.S.A., 1973; pp. 140–154.
64. Alekseev, V.R. *Naledevedeniye* (Icing Studies). Siberian Branch RAS Publ.: Novosibirsk, Russia, 2007 (in Russian).
65. Clark, I.D.; Lauriol, B. Aufeis of the Firth River basin, Northern Yukon, Canada: Insights into permafrost hydrogeology and karst. *Arctic Alp Res* **1997**, *29(2)*, 240–252.
66. Murton, J.B.; Edwards, M.E.; Lozhkin, A.V.; Anderson, P.M.; Savvinov, G.M.; Bakulina, N.; Bondarenko, O.V.; Cherepanova M.V.; Danilov, P.P.; Boeskorov, V.; Goslar, T.; Grigoriev, S.; Gubin, S.V.; Korzun, J.A.; Lupachev, A.V.; Tikhonov, A.; Vasilieva, G.V.; Zanina, O.G. Preliminary paleoenvironmental analysis of permafrost deposits at Batagaika megaslump, Yana Uplands, northeast Siberia. *Quatern Res* **2017**, *87(2)*, 314–330.
67. Opel, T.; Wetterich, S.; Meyer, H.; Dereviagin, A.Y.; Fuchs, M.C.; Schirrmeister, L. Ground-ice stable isotopes and cryostratigraphy reflect late Quaternary palaeoclimate in the Northeast Siberian Arctic (Oyogos Yar coast, Dmitry Laptev Strait). *Clim Past* **2017**, *13*, 587–611. DOI: 10.5194/cp-13-587-2017.
68. Carey, S.K.; Woo, M.K. Hydrology of two slopes in subarctic Yukon, Canada. *Hydrol Process.* **1999**, *13(16)*, 2549–2562. DOI: 10.1002/(SICI)1099-1085(199911)13:16<2549::AID-HYP938>3.0.CO;2-H.
69. Heginbottom, J.A. Permafrost mapping: a review. *Progress Phys Geogr.* **2000**, *26(4)*, 623–642. DOI: 10.1191/0309133302pp355ra.
70. Reggiani, P.; Rientjes, T.H.M. Flux parametrization in the representative elementary watershed approach: Application to a natural basin. *Water Resour Res.* **2005**, *41(4)*, W04013. DOI: 10.1029/2004WR003693.
71. Flügel, W.-A. Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Bröl, Germany. *Hydrol Process.* **1995**, *9*, 423–436.
72. Walvoord, M.A.; Voss, C.I.; Wellman, T.P. Influence of permafrost distribution on groundwater flow in the context of climate-driven permafrost thaw: Example from Yukon Flats Basin, Alaska, United States. *Water Resour Res.* **2012**, *48*, W07524. DOI:10.1029/2011WR011595.
73. Prowse T. Northern hydrology: an overview. In *Northern Hydrology: Canadian Perspectives*; Prowse, T., Ommanney, C., Eds.; NHRI Science Report No. 1., 1990; pp. 1–36.
74. Duguay, C.R.; Pietroniro, A. Introduction. In *Remote Sensing in Northern Hydrology: Measuring Environmental Change*; Duguay, C.R., Pietroniro, A., Eds. Geophysical Monograph Series 163, 2005; pp. 1–5. DOI: 10.1029/163GM02.
75. Tetzlaff, D.; Buttle, J.; Carey, S.K.; McGuire, K.; Laudon, H.; Soulsby, C. Tracer-based assessment of flow paths, storage and runoff generation in northern catchments: a review. *Hydrol Process.* **2014**, *29*, 3475–3490. DOI: 10.1002/hyp.10412.
76. Flowers, G.E.; Björnsson, H.; Pállson, F. New insights into the subglacial and periglacial hydrology of Vatnajökull, Iceland, from a distributed physical model. *J Glac.* **2003**, *49(165)*, 257–270. DOI: 10.3189/172756503781830827.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 13 May 2019 doi:10.20944/preprints201905.0154.v1

77. Sund, M. Polar hydrology. Report 2–2008. Norwegian Water Resources and Energy Directorate: Oslo, Norway; 2008.
78. Tetzlaff, D.; Piovano, T.; Ala-Aho, P.; Smith, A.; Carey, S.; Marsh, P.; Wookey, P.A.; Street, L.E.; Soulsby, C. Using stable isotopes to estimate travel times in a data-sparse Arctic catchment: Challenges and possible solutions. *Hydrol Process*. **2018**, *32*, 1936–1952. DOI: 10.1002/hyp.13146.
79. Bagard, M.L.; Chabaux, F.; Pokrovsky, O.S.; Viers, J.; Prokushkin, A.S.; Stille, P.; Rihs, S.; Schmitt, A.D.; Dupré, B. Seasonal variability of element fluxes in two Central Siberian rivers draining high latitude permafrost dominated areas. *Geochim Cosmochim Acta*. **2011**, *75*, 3335–3357. DOI: 10/1016/j.gca.2011.03.024.
80. Taupp, M.; Constan, L.; Hallam, S.J. The biogeochemistry of anaerobic methane oxidation. In *Handbook of Hydrocarbon and Lipid Microbiology*; Timmis, K.N., Ed. Springer: Berlin-Heidelberg, Germany, 2010; pp. 887–907. DOI: 10.1007/978-3-540-77587-4_63.
81. Mann, P.J.; Eglinton, T.I.; McIntyre, C.P.; Zimov, N.; Davydova, A.; Vonk, J.E.; Holmes, R.M.; Spencer, R.G.M. Utilization of ancient permafrost carbon in headwaters of Arctic fluvial networks. *Nat Commun.* **2015**, *6*, 7856. DOI: 10.1038/ncomms8856.
82. Frey, K.E.; Sobczak, W.V.; Mann, P.J.; Holmes, R.M. Optical properties and bioavailability of dissolved organic matter along a flow–path continuum from soil pore waters to the Kolyma River mainstem, East Siberia. *Biogeosci.* **2016**, *13*, 2279–2290. DOI: 10.5194/bg-13-2279-2016.
83. Karra, S.; Painter, S.L.; Lichtner, P.C. Three-phase numerical model for subsurface hydrology in permafrost-affected regions (PFLOTRAN–ICE v.1.0). *The Cryosphere* **2014**, *8*, 1935–1950. DOI: 10.5194/tc-8-1935-2014.
84. McKenzie J.M.; Voss, C.I.; Siegel, D.I. Groundwater flow with energy transport and water-ice phase change: Numerical simulations, benchmarks, and application to freezing in peat bogs. *Adv Water Resour* **2007**, *30(4)*, 966–983. DOI: 10.1016/j.advwatres.2006.08.008.
85. Orgogozo, L.; Prokushkin, A.S.; Pokrovsky, O.; Grenier, C.; Quintard, M.; Viers, J.; Audry, S. Water and energy transfer modeling in a permafrost-dominated, forested basin catchment of Central Siberia: The key role of rooting depth. *Permafr Periglac Process*. **2019**, *30(2)*, 75–89. DOI: 10.1002/ppp.1995.
86. Semenova, O.; Vinogradov, Yu.; Vinogradova, T.; Lebedeva, L. Simulation of soil profile heat dynamics and their integration into hydrological modelling in a permafrost zone. *Permafr Periglac Process*. **2014**, *25*, 257–269. DOI: 10.1002/ppp.1820.
87. Hülsmann, L.; Geyer, T.; Schweitzer, C.; Priess, J.; Karthe, D. The effect of subarctic conditions on water resources: Initial results and limitations of the SWAT model applied to the Kharaa River basin in Northern Mongolia. *Environ Earth Sci.* **2015**, *73*, 581–592. DOI: 10.1007/s12665-014-3173-1.
88. Fabre, C.; Sauvage, S.; Tananaev, N.; Srinivasan, R.; Teisserenc, R.; Sánchez Pérez, J.M. Using modeling tools to better understand permafrost hydrology. *Water* **2017**, *9*, 418. DOI:10.3390/w9060418.
89. Sukhodrovsky, V.L. *Ekzogennoye rel'efoobrazovaniye v kriolitozone* (Exogenous morphogenesis in permafrost). Nauka: Moscow, USSR; 1979 (in Russian).