LUND UNIVERSITY

The role of the hydrological cycle in forest ecosystems

flow path, nutrient cycling and water-carbon interaction

Yan, Yanzi

2019

[Link to publication](#)

The role of the hydrological cycle in forest ecosystems

Flow path, nutrient cycling and water-carbon interaction

YANZI YAN

DEPARTMENT OF PHYSICAL GEOGRAPHY AND ECOSYSTEM SCIENCE | LUND UNIVERSITY

The role of the hydrological cycle in forest ecosystems

Flow path, nutrient cycling and water-carbon interaction

Yanzi Yan

Department of Physical Geography and Ecosystem Science,
Lund University, Sweden

LUND

UNIVERSITY

DOCTORAL DISSERTATION

Faculty opponent
Professor John P. Wilson
Spatial Science Institute, University of Southern California

Organization LUND UNIVERSITY	Document name DOCTORAL DISSERTATION
	Date of issue 1 November 2019
Author(s) Yanzi Yan	Sponsoring organization

Title and subtitle
The role of hydrological cycle in forest ecosystem – flow path, nutrient cycling and water-carbon interaction

Abstract

Forest ecosystems, covering over a third of land on the Earth, play a significant role in the global hydrological cycle, and influence soil erosion and climate change. However, the distribution, movements, quality of water, and hydrological processes in forested ecosystems are not well understood yet. This thesis aims to improve our understanding of the interaction between forest ecosystems and water cycle from the perspective of flow path, nutrient cycling, and carbon – water interactions.

Flow path is particularly important for the study of water storage and distribution, and solute transport and attenuation. However, in dense forest areas, flow path is usually hard to detect from terrain models due to large noise in elevation data, e.g. large sinks. Spurious sinks hinder water flowing downslope and thus likely result in unrealistic flow path estimation. An algorithm that can tackle spurious sinks without altering elevation was proposed and shown to be able to estimate flow path more accurately than traditional methods for different terrain forms.

Besides the problem of flow path estimation, the evaluation of flow path estimation has usually been done for the whole catchment, ignoring the variability of the disagreement between estimated flow path and observations among different land cover, soil type, and slopes within a catchment. A number of culverts investigated in fields have thus been used and taken as observations of stream locations for the assessment of flow path evaluation. The results showed that the uncertainty of flow path estimation is strongly related to soil hydraulic productivity, vegetation cover, and slope.

Furthermore, nutrient cycling can significantly affect the quality of water. Water is observed getting browner in (sub)arctic regions due to elevated concentration of dissolved organic carbon (DOC). However, it is still not well known how catchment morphometric, e.g. hydrologic connectivity, could affect the distribution and transportation of DOC from terrestrial systems to streams. A systematic analysis of the relationship between catchment morphometric and DOC concentration was thus carried out, and the results showed that smaller catchment size, shorter flow length, and younger catchments tend to have higher DOC concentrations.

Moreover, remote sensing observations have revealed that Amazon rainforests are resilient to droughts and could maintain photosynthesis productivity during dry season. Light, leaf phenology etc. have been reported to drive the seasonality of vegetation productivity in tropical forests. Plant use of groundwater with deep roots could sustain evapotranspiration during the dry season and thus could drive the dry season greening. However, the role of groundwater in the resilience of tropical forests to drought is not well studied yet. A global dynamic vegetation model, i.e. LPJ-GUESS model, was implemented to simulate water and carbon fluxes for tropical forests. Model simulations with groundwater introduced were found to be able to reproduce the seasonality of photosynthesis productivity of tropical forests. In addition, model simulations showed that groundwater substantially sustains tropical forest productivity, especially for wet and seasonally dry areas if future climate is getting drier. However, it seems that groundwater doesn't make large differences for forest productivity when future climate is getting wetter.

Key words Flow path, nutrient cycling, carbon-water interactions, forest ecosystem

Classification system and/or index terms (if any)

Supplementary bibliographical information	**Language** English
ISSN and key title	**ISBN** 978-91-985016-5-0 (print) 978-91-985016-6-7 (PDF)
Recipient's notes	**Number of pages** 67	Price
	Security classification	

The role of the hydrological cycle in forest ecosystems

flow path, nutrient cycling and water-carbon interaction

Yanzi Yan

LUND
UNIVERSITY

Front cover: Colour painting, 'Vegetation and water in forests' by Xiaoyi Yan

Back cover: Fenghuang Gu Cheng, photo by Yanzi Yan

Faculty of Science
Department of Physical Geography and Ecosystem Science

Life is not hard to manage when you've got nothing to lose.

- Ernest Miller Hemingway

List of publications

I. **Yanzi Yan**, Jing Tang, Petter Pilesjö. (2018). A combined algorithm for automated drainage network extraction from digital elevation models. *Hydrological processes*, 32(10), 1322-1333.

II. **Yanzi Yan**, William Lidberg, David E. Tenenbaum, Petter Pilesjö . (2019). The accuracy of drainage network delineations as a function of environmental factors: a case study in central and northern Sweden. Submitted.

III. Pearl Mzobe, **Yanzi Yan**, Martin Berggren, Petter Pilesjö, David Olefedt, Erik Lundin, Nigel Roulet, Andreas Persson, (2019) Morphometric control on dissolved organic carbon in subarctic streams. Submitted.

IV. **Yanzi Yan**, Stefan Olin, Magnus Persson, Petter Pilesjö, Feng Tian, Zhendong Wu, Minchao Wu, Wenxin Zhang, Adrian Gustafson, Antje Gärtner, Anders Ahlström. (2019). The role of groundwater in resilience of Amazon rainforest to drought. Manuscript

List of contributions

I. Yanzi Yan designed the study, performed all the computations and data analysis, and wrote the first draft of the manuscript.

II. Yanzi Yan led the study design, performed all the computations and data analysis and wrote the first draft of the manuscript.

III. Yanzi Yan performed the computations for different catchment morphemic factors, discussed and commented on the draft paper.

IV. Yanzi Yan participated in the major part of study design, performed all the simulations and data analysis, and wrote the first draft of the manuscript.

All papers are reproduced with permission of their respective publishers.

Abstract

Forest ecosystems, covering over a third of land on the Earth, play a significant role in the global hydrological cycle, and influence soil erosion and climate change. However, the distribution, movements, quality of water, and hydrological processes in forested ecosystems are not well understood yet. This thesis aims to improve our understanding of the interaction between forest ecosystems and water cycle from the perspective of flow path, nutrient cycling, and carbon – water interactions.

Flow path is particularly important for the study of water storage and distribution, and solute transport and attenuation. However, in dense forest areas, flow path is usually hard to detect from terrain models due to large noise in elevation data, e.g. large sinks. Spurious sinks hinder water flowing downslope and thus likely result in unrealistic flow path estimation. An algorithm that can tackle spurious sinks without altering elevation was proposed and shown to be able to estimate flow path more accurately than traditional methods for different terrain forms.

Besides the problem of flow path estimation, the evaluation of flow path estimation has usually been done for the whole catchment, ignoring the variability of the disagreement between estimated flow path and observations among different land cover, soil type, and slopes within a catchment. A number of culverts investigated in fields have thus been used and taken as observations of stream locations for the assessment of flow path evaluation. The results showed that the uncertainty of flow path estimation is strongly related to soil hydraulic productivity, vegetation cover, and slope.

Furthermore, nutrient cycling can significantly affect the quality of water. Water is observed getting browner in (sub)arctic regions due to elevated concentration of dissolved organic carbon (DOC). However, it is still not well known how catchment morphometric, e.g. hydrologic connectivity, could affect the distribution and transportation of DOC from terrestrial systems to streams. A systematic analysis of the relationship between catchment morphometric and DOC concentration was thus carried out, and the results showed that smaller catchment size, shorter flow length, and younger catchments tend to have higher DOC concentrations.

Moreover, remote sensing observations have revealed that Amazon rainforests are resilient to droughts and could maintain photosynthesis productivity during dry season. Light, leaf phenology etc. have been reported to drive the seasonality of vegetation productivity in tropical forests. Plant use of groundwater with deep roots could sustain evapotranspiration during the dry season and thus could drive the dry season greening. However, the role of groundwater in the resilience of tropical forests to drought is not well studied yet. A global dynamic vegetation model, i.e. LPJ-GUESS model, was implemented to simulate water and carbon fluxes for tropical forests. Model simulations with groundwater introduced were found to be able to reproduce the seasonality of photosynthesis productivity of tropical forests. In addition, model simulations showed that groundwater substantially sustains tropical forest productivity, especially for wet and seasonally dry areas if future climate is getting drier. However, it seems that groundwater doesn't make large differences for forest productivity when future climate is getting wetter.

Sammanfattning

Skogens ekosystem täcker en tredjedel av jordens yta och spelar en signifikant roll i den globala hydrologiska cykeln, liksom avseende erosion och klimatförändringar. Vattnets fördelning, liksom dess lagring, rörelse, kvalité och andra hydrologiska processer i skogsområden är dock ännu inte helt utredd. Denna avhandling syftar till att förbättra förståelsen för samspelet mellan skogens ekosystem och vattnets cykel med fokus på flödesvägar, transport av näringsämnen samt kol-vatten-växelverkan. Flödesvägar är i synnerhet viktiga för att studera vattenlagring och distribution och transport av lösta ämnen, samt dess dämpande effekt. I täta skogsområden är dock flödesvägar vanligtvis svåra att upptäcka utifrån digitala terrängmodeller på grund av stort brus i höjddatan, t.ex. stora "falska" sänkor. Falska sänkor hindrar modellering av vattnets avrinning och resulterar därför sannolikt i orealistiska uppskattningar av flödesvägar. En algoritm som kan hantera falska sänkor utan att förändra höjddata föreslogs därför, och visade sig kunna uppskatta flödesvägar mer exakt än konventionella metoder för olika terrängformer.

Utöver problemet med uppskattning av flödesvägar är det ett inte optimalt att utvärderingar av flödesvägsberäkningar vanligtvis görs för hela avrinningsområden, och därmed försummar variationen i överensstämmelse mellan uppskattad flödesväg och olika markanvändning, jordtyp och lutningar inom ett avrinningsområde. Ett antal kulvertar som undersökts vid fältstudier har därför använts som observationer av sanna flödesvägar, och därefter använts för bedömning och utvärdering av flödesvägar i olika terräng. Resultaten visade att osäkerheten i uppskattningen av flödesvägar är starkt relaterad till markhydraulisk produktivitet, vegetationstäckning och sluttningar. Dessutom kan näringscykler påverka vattenkvaliteten avsevärt.

Vatten blir ibland brunare i (sub-)arktiska regioner på grund av förhöjd koncentration av löst organiskt kol (DOC). Det är dock fortfarande inte klargjort hur morfometri, t.ex. uppsamling genom hydrologisk anslutning kan påverka distribution och transport av DOC från marksystem till vattendrag. En systematisk analys av förhållandet mellan morfometri och DOC-koncentration utfördes därför, och resultaten visade att mindre storlek på avrinningsområden, kortare flödeslängd och yngre avrinningsområden tenderar att ha högre DOC-koncentrationer.

Observationer med hjälp av fjärranalys har indikerat att Amazonas regnskogar är motståndskraftiga mot torka och kan upprätthålla fotosyntesproduktiviteten under torrsäsong. Ljus och bladfenologi har rapporterats driva säsongsindelningen för vegetationsproduktivitet i tropiska skogar. Växternas användning av grundvatten genom djupa rötter kan upprätthålla evapotranspiration under den torra säsongen och kan därmed göra torrsäsongen grönare. Grundvattnets roll i de tropiska skogarnas motståndskraft mot torka är dock inte fullt undersökt ännu. En global dynamisk vegetationsmodell, dvs. LPJ-GUESS-modellen, implementerades för att simulera vatten- och kolflöden för tropiska skogar. Modellsimuleringar med grundvatten som infördes visade sig kunna reproducera säsongsindelningen av fotosyntesproduktiviteten i tropiska skogar. Dessutom visade modellsimuleringar att grundvattnet väsentligen kan upprätthålla skogsproduktiviteten i tropisk skog, särskilt för våta och säsongstorra områden om det framtida klimatet blir torrare. Det verkar dock som att grundvattnet inte gör någon större skillnad för skogsproduktiviteten om det framtida klimatet blir våtare.

摘要

森林生态系统占据地球陆地面积的三分之一，在全球水循环中扮演着十分重要的角色，影响着土壤侵蚀和气候变化。然而，对森林水的质量、分布、运动及其水文过程机制的认知与研究，目前还较为不足。本篇论文的主要目标是从碳-水耦合、土壤养分循环和水流路径这三方面展开研究，以进一步提高对森林生态系统水循环过程的理解。

水流路径对水的存储和分布，溶质的运输和衰减起着至关重要的作用。 然而，在茂密森林地区，高程数据出现较大的观测误差，通常表现为地表上许多伪洼地的分布。这些洼地阻碍了水流沿坡向下流动，从而很难提取较为精确的水流路径及其相应水系的分布。本文因此提出了一种在不改变高程的情况下处理洼地的算法，并证明了该算法对不同地形形态的水流流径提取都比传统方法更为准确。

除了上述的水流路径提取问题外，通常水流路径提取的评估都是针对一整个流域而言。这种粗糙的估计方法通常忽略了流域内不同土地覆被、土壤类型和坡度对水流路径提取精度的影响。水流路径提取精度的空间差异，涉及到流域内水资源管理措施的效率，以及水文模型模拟的不确定性分析。在本论文里，利用野外实测的涵洞数据（近似为河流实际位置），对不同植被类型，土壤类型以及坡度内的水流提取精度进行评估。结果表明，水流路径提取的不确定性与土壤水力生产力、植被覆盖度、坡度等因素密切相关。

此外，土壤养分循环是影响水质的重要因素。在(亚)北极地区，由于溶解有机碳(DOC)浓度升高，水体显示褐色。然而，流域的形态特征，例如水文连通性，是如何影响 DOC 从陆地系统到河网的分布和运输，目前尚不清楚。因此，我们对流域形态特征与 DOC 浓度之间的关系进行了系统性的分析，其结果表明，较小的流域规模、较短的水流长度以及较年轻的流域往往具有较高的 DOC 浓度。

遥感观测显示，亚马逊热带雨林对干旱具有一定抵抗力，在旱季可以维持光合作用的生产力。据报道，光、叶物候等对热带森林植被生产力的季节性具有重要的驱动作用，植物利用深根地下水可以维持旱季的蒸散，从而促进旱季绿化。

然而，地下水在热带森林抗旱能力中的作用尚未得到很好的研究。采用 LPJ-GUESS 全球动态植被模型，模拟热带森林的水分和碳通量。引入地下水的模型模拟可以重现热带森林光合作用生产力的季节性。此外，模型模拟显示，地下水在很大程度上维持着热带森林的生产力，特别是在未来气候越来越干燥的潮湿和季节性干旱地区。然而，当未来气候变得更加湿润时，地下水对森林生产力的影响似乎并不大。

Table of Contents

1 Introduction

1.1 Hydrological cycle

Figure 1.1 shows the hydrological cycle in which water leaves the atmosphere and falls to earth as precipitation where it enters surface waters or infiltrates into the soil surface, or further percolates through the soil layer to underlying ground water and eventually is taken back into the atmosphere by transpiration and evaporation to begin the cycle again. Precipitation before falling to the ground may be intercepted by plant foliage and eventually evaporate back to the atmosphere. In short, there are three main components within the hydrologic cycle, namely precipitation, runoff, and evapotranspiration. Runoff consists of surface runoff and subsurface runoff. As shown in Fig.1.1, surface runoff is the part reaching the drainage basin outlet via overland flow and stream channels, while subsurface runoff is the sum of interflow and groundwater flow (Beven, 2011). Interflow indicates water infiltrating the soil surface and then moves laterally through the upper soil horizons towards the stream channels. Different components of hydrologic processes vary spatially and temporally worldwide due to the combined effects of e.g. climate, land cover, and topography.
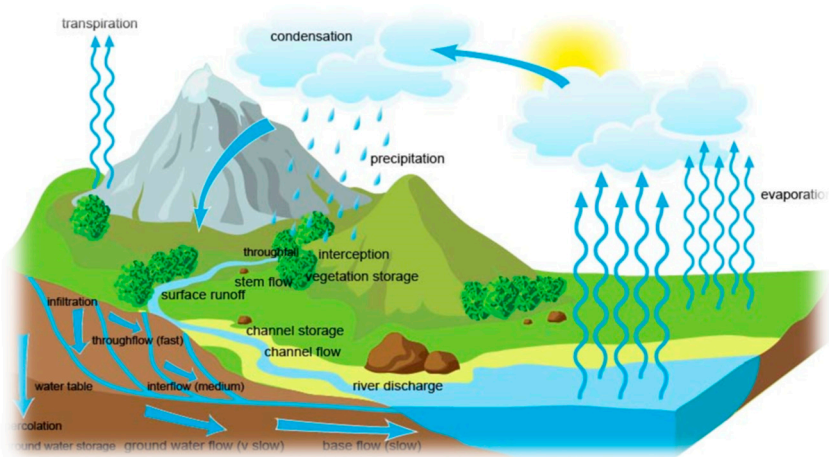

Figure 1.1. Hydrologic cycle.
(Source:https://www.alevelgeography.com/drainage-basin-hydrological-system/)

1.2 Hydrologic cycle and forests

About one third of the earth's land surface is covered by forests. Forest ecosystems significantly affect the global hydrological cycle (Sedell et al., 2000). The presence, quality, distribution of water and hydrological processes shapes not only the physical shape but also the biological parts of the ecosystems and plays a key role in forest-dominated ecosystem functions and processes (NRC,2008).

Flow path, represented as drainage network vectors, are lines along which fluvial processes act to transport water and mineral material out of a local region under the force of gravity (O'Callaghan & Mark, 1984). Generally speaking, flow path is determined based on topography as water moves downslope towards the catchment outlet. With the rapidly increasing availability of topographic information as digital elevation models (DEMs), there have been many studies on DEM-based flow path estimation algorithms (Freeman, 1991; Gallant & Hutchinson, 2011; Holmgren, 1994; Ibbitt et al., 1999; O'Callaghan & Mark, 1984; Orlandini et al., 2003; Pilesjö & Hasan, 2014; Quinn et al., 1991; Tarboton, 1997; Turcotte et al., 2001; Wilson & Gallant, 2000; Xiong et al., 2014; Zhou et al., 2011). However, the flow path estimation still remains challenging in forested areas since the surface over forested areas is usually noisy, creating numerous small sinks and barriers that further complicate the estimation. In addition, the mapped elevated surface for forested areas is likely to include forest canopy rather than the ground surface required for flow routing, and the gaps in vegetation could create large sinks that pose difficulties for flow routing (Metz et al., 2011a). The problem of sinks on a surface during flow path estimation is explained in detail below.

In addition, the number of flow paths identified can depend on the environmental conditions and the objectives of the investigation. As mentioned above most commonly used algorithms determine the flow path only based on topographic information, ignoring the effect of other environmental conditions, like land cover and soil type on water pathways, which may cause different degrees of disagreement between estimated flow path and field observations. The lack of the information about the variation of the disagreement mentioned can often cause ineffective water resource management and incomplete uncertainty analysis of hydrologic modelling.

Furthermore, as hydrological flows drive the movement and attenuation of nutrients, forest ecosystem nutrient cycling is to a large extent controlled by flow path and associated catchment environment, including forms of precipitation (i.e. rain, snow, and fog), soil and air temperature, and geo-morphometric features of forest-dominated

catchments. Typically, organic carbon is delivered via overland flow and subsurface pathways (Findlay, 1995). Many biogeochemical studies have quantified lateral export of carbon from terrestrial land to inland waters and found that catchment characteristics like aspect, slope, and stream order have impacted the movement, concentration, and fluxes of dissolved organic carbon (DOC). However, there is still a lack of a systematic study of different impacts of catchment characteristics on DOC variability.

Moreover, forests as a crucial part of the Earth's carbon stock and flow play an integral part in the carbon cycle and thus are a stabilising force for the climate. Climate change can affect terrestrial and marine ecosystem, which in turn has impacts on both the water and carbon cycles and then feeds back to the climate. However, the coupling processes between terrestrial carbon and hydrological process are extremely complex and far from well understood. (Matsui et al., 2004). Droughts can cause tree death and tree takes long time to regrow. The recovery time for forest biomass lost through extreme events are particularly long. While forests were also argued resilient to climate change since trees were observed to survive during drought periods due to their deep roots accessing deep soil water and groundwater (Barbeta & Peñuelas, 2017).

1.3 Flow path

1.3.1 Flow path estimation

As mentioned above, flow path is a vector form of drainage network. Thus, the estimation of flow path is considered as drainage network extraction in this thesis. In general, there are three categories of drainage network extraction algorithms from DEMs: morphology-based methods (Band, 1986; Greysukh, 1967; Heine et al., 2004; Montgomery & Dietrich, 1992; Peucker & Douglas, 1975; Rodríguez-Iturbe & Rinaldo, 2001; Tribe, 1992; Yoeli, 1984); hydrology-based methods (Freeman, 1991; Gallant & Hutchinson, 2011; Holmgren, 1994; Ibbitt et al., 1999; O'Callaghan & Mark, 1984; Orlandini et al., 2003; Pilesjö & Hasan, 2014; Quinn et al., 1991; Tarboton, 1997; Turcotte et al., 2001; Xiong et al., 2014; Zhou et al., 2011), and combinations of morphology-based and hydrology-based methods (Passalacqua et al., 2010; Pirotti & Tarolli, 2010; Sofia et al., 2011; T. Wang, 2014). Among them, hydrology-based algorithms are the most commonly used for drainage network extraction since they are able to simulate continuous stream flow over the terrain. The algorithms determine the proportion of surface water transported/flowing to each neighbouring downslope cell and then calculate accumulated flow of all cells flowing into each downslope cell in the

output raster. Based on the cumulative flow from upstream cells, the minimum value of flow accumulation for channel initiation is manually set to extract the drainage networks.

However, when implementing the hydrology-based algorithms, spurious sinks over surface block the flow in the sinks and thus have great impact on the drainage network extraction (Hutchinson, 1989). To solve the problem of spurious sinks, it requires pre-processing of DEMs in order to remove sinks. The most widespread methods for handling sinks are sink-filling (Jenson & Domingue, 1988; Martz & De Jong, 1988; O'Callaghan & Mark, 1984; L. Wang & Liu, 2006) and/or sink carving/breaching (Lindsay, 2015; Lindsay & Creed, 2005; Martz & Garbrecht, 1999; Rieger, 1998). Although these sink treatments ensure full drainage, they alter the elevation data in the DEMs, resulting in inconsistency between the altered-terrain and the original surface. In addition, instead of spurious sinks, some sinks in the DEMs are representation of natural terrain, e.g. lakes. Most lakes in the world are open lakes whose water eventually empties into the sea. However, some lakes are closed lakes in which water stay inside the sinks and thus they should be excluded when pre-processing the DEMs. Traditional sink treatments (i.e. sink filling and/or sink breaching, Fig.1.2) consider all sinks as spurious and thus remove all actual sinks either open or closed lakes, resulting in unrealistic drainage networks. In addition, traditional sink treatments also cause the problem of unrealistic parallel drainage networks (Hutchinson, 1989; Yamazaki et al., 2012). Therefore, it is questionable if methods based on sink removal can be applied for appropriate flow routing determination and related hydrological and biographical applications.

The Least-Cost Paths (LCP) through un-altered terrain and out of sinks (Fig.1.2) is an alternative approach to the modification of elevation for sink removal as mentioned above. This LCP approach has provided more accurate flow routing through large, widely distributed sinks with less artefacts than traditional sink filling (Kinner et al., 2005). However, the previous LCP implementations (i.e. LCP algorithm based Single Flow Direction (SFD) or based on Multiple Flow Direction (MFD) were only able to simulate one flow pattern, i.e. either single flow pattern or multiple flow pattern. Nevertheless, terrain surfaces in the real world are usually very complicated including both convergent and divergent flow patterns. Therefore, an algorithm that is able to tackle the problem of sinks and to simulate both convergent and divergent flow is required for better drainage network delineation over complicated surface in the real world.
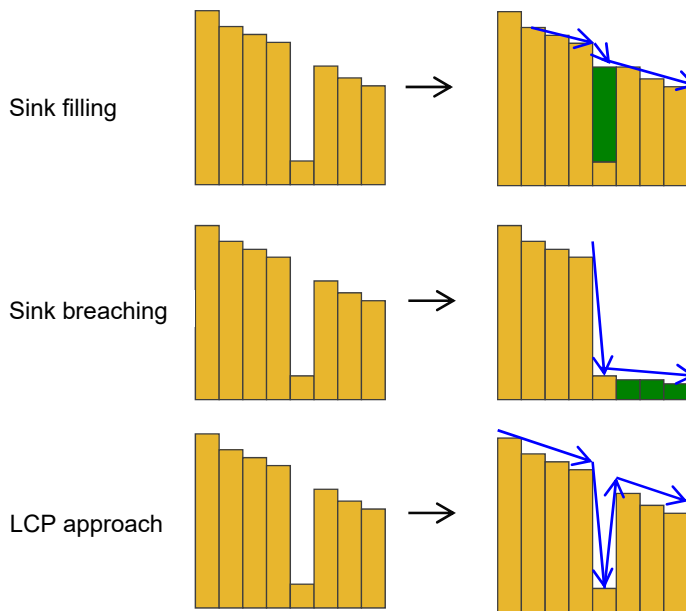
Figure 1.2. A graphic representation of different sink treatments.

1.3.2 Variability of disagreement in flow path estimation

Since flow path/drainage network is usually estimated based on DEMs, most previous studies argued that the complexity of topography e.g. DEM resolution has a significant effect on the uncertainty of estimated flow path (M. Wu et al., 2017). However, varying vegetation, soil type, etc., affecting the hydrologic environment, could also have impacts on the drainage network delineation. It is known that the infiltration rate of soil, the water content in different soils and drainage channels, etc., strongly influence runoff pattern (Dietrich et al., 1992; O'Callaghan & Mark, 1984; Veihmeyer & Hendrickson, 1931). In addition, the quality of a DEM is subject to variation depending on land cover types and terrain characteristics (Adams & Chandler, 2002; Hodgson et al., 2005). Thus, the uncertainty of delineated drainage network could, to some extent, vary spatially as a function of the heterogeneity of these environmental elements. Lacking such knowledge, we may easily ignore the potential fact that the uncertainty of biogeochemical process modelling may be due to the uncertainty of flow path estimation (Chaves & Nearing, 1991).

Although some studies observed that vegetation, soil type and topography might have effects on the results of delineated drainage network, they did not explain, how and to what extent, features of these environmental factors might affect the uncertainty of drainage network delineation. In addition, even though the variability of the uncertainty

of drainage network delineation was noticed within a catchment, most studies still only evaluate the uncertainty of drainage network delineation at catchment scale. This assessment has substantially limited the ability to communicate detailed information of the quality of delineated drainage network to users (Johnston & Timlin, 2000) and thus could mislead water resource management within a catchment, e.g. ineffective irrigation system design for farming (Bhattacharya & Michael, 2006; Karásek et al., 2015; Molle et al., 2007; Young et al., 2004).

1.4 Nutrient cycling

Freshwaters represent a significant and dynamic component in the global carbon (C) cycle. Inland waters are recognized as significant dynamic zones in the C cycle, particularly in terms of C outgassing and storage (Cole et al., 2007). Inland waters are estimated to emit between 1.2 and 2.1 Pg C CO_2 to the atmosphere annually (Aufdenkampe et al., 2011; Raymond et al., 2004; Tranvik et al., 2009). Globally, 2.7 Pg yr-1 of organic C is exported from terrestrial ecosystems to inland waters (Battin et al., 2009). Many northern lakes and streams have experienced an increase in the amount of C they receive, with elevated dissolved organic C (DOC) concentrations being linked to brownification in Sweden (Graneli, 2012; Jonsson et al., 2015). Evans and Thomas (2016) found that there has been a doubling, in some cases a threefold increase, of DOC in rivers in northern Europe and America. However, the terrestrial-riverine interactions that control these DOC concentrations remain understudied (Hotchkiss et al., 2015; Li et al., 2017; Regnier et al., 2013). There have been numerous studies on the vertical fluxes of C, i.e. between water, atmosphere and sediments, while there are few studies about lateral C fluxes from terrestrial to inland waters.

Hydrologic connectivity (Bracken et al., 2013) and related catchment geomorphology have been found to control carbon concentrations in inland waters, i.e. DOC concentrations. Hotchkiss et al. (2015) found that stream size influences the processes and emissions of CO_2 from a stream, and that terrestrially derived organic C is a particularly important driver of the metabolic fluxes in small streams. Lauerwald et al. (2015) used stream orders three and higher for their assessment of global CO_2 evasion from streams. In the boreal region, Ågren et al., (2007) found that smaller streams have higher DOC concentrations compared to larger ones. Distance, i.e. travel time, also influences the DOC concentration with export being lower for distal subcatchments (ibid.). Carbon and nitrogen cycling processes can vary along a topographical gradient as found in a central Amazon forest (Luizão et al., 2004).

However, so far these studies have been focused on temperate and boreal catchment. Arctic ecosystems have distinct climate, vegetation, soils etc., from boreal, temperate and tropical regions and the mechanisms controlling DOC concentrations in (sub)arctic ecosystems were poorly understood. In addition, arctic ecosystems are found more vulnerable to climate change than other forested regions of the world (Meehl et al., 2007), implying that there might be highly variability of arctic ecosystem's response to climate at different catchments. Therefore, it is important to perform a systematic analysis of catchment characteristics and to see if the variability of DOC concentrations in (sub) arctic catchment is controlled by catchment geomorphology. Such analysis also allows an assessment of carbon delivery potential and the refinement of current carbon states at catchment level.

1.5 Water-carbon interactions

Amazon rainforest is the Earth's largest forest ecosystem, and the changes in the biophysical state of the Amazon rainforest significantly influence global dynamics of climate, carbon and water (Huete et al., 2006). However, its vulnerability to drought remains poorly understood, as conflicting results have been reported (Ahlström et al., 2017; Brando et al., 2010; Malhi et al., 2009; Phillips et al., 2009; Saleska et al., 2007).

Remote sensing observations revealed a basin-wide increase in photosynthetic activity (Saleska et al., 2016), and eddy flux tower and filed observations also showed an increase in leaf area correlated to solar radiation and sustained evapotranspiration (ET) in the dry season (Huete et al., 2006; Myneni et al., 2007). Such unexpected dry season greening, seems to suggest that light, instead of water, may drive the forest seasonality in tropical wet climate.Liu et al. (2018) have found that Amazon forest greening during the 2015 drought was partly due to the mitigation effect of higher absorbed solar radiation on the photosynthesis. Leaf quality and quantity are also argued to play an important role in regulating carbon fluxes during the dry season. Camera observations and leaf-level measurements revealed that new leaves growing, synchronized with dry-season litter fall, have higher photosynthetic capacity and therefore light use efficiency (Manoli et al., 2018; J. Wu et al., 2016). In addition, the fact that deep tree roots allow continuous access to deep soil water when near surface soil layer dries during seasonally drought is critical for maintaining dry-season gross primary production (GPP) (Baker et al., 2008; Poulter et al., 2009). Furthermore, many studies have revealed that plant use of groundwater with deep roots plays a significant role in evapotranspiration at sites

with a pronounced dry season (Barbeta & Peñuelas, 2017; Christoffersen et al., 2014; Fan & Miguez-Macho, 2010).

Although the mechanisms of upward capillary flux from groundwater and deep root uptake are complementary mechanisms of water supply and can both sustain ET during the dry season, their relative importance is site-dependent. In fact, most studies about controlling mechanisms in the Amazon rainforest greening in the dry season are site-based. Therefore, the regional impact of groundwater in the Amazon remains un-investigated. Furthermore, given the uncertain future climate scenarios, it is of significant importance to investigate the role of groundwater in the growth of Amazon rainforest under climate change.

2 Aims and objectives

Forests cover a third of all land on Earth, provide habitats for biodiversity and livelihoods for humans, and prevent soil erosion and mitigate climate change. The distribution, storage, movement and quality of water and the hydrologic processes within forested areas play a key role in forest-dominated ecosystem functions and processes (NRC, 2008). The objective of this PhD thesis is to enhance our understanding of the role of hydrological processes in forested ecosystems. The aims of this thesis are to:

I.   Improve the flow path estimation in forested areas based on digital elevation models.

II. Assess the variability of the uncertainty of flow path estimation in forest-dominated catchments.

III. Study the impacts of hydrologic flow and associated catchment characteristics on nutrient cycling (e.g. DOC fluxes) in (sub)arctic catchments.

IV. Improve model performance in coupling processes of water-carbon cycle in tropical forests.

3 Methods

3.1 LCP algorithm combined with TFM algorithm

The "normal way" for a person to determine a drainage basin is first to define the point where the river leaves the basin. Similarly, the LCP algorithm (A* Search) (Hart et al., 1968; Metz et al., 2011b) starts with defined potential outlet points. On gridded elevation models, potential outlets are grid cells along the map boundaries or cells whose neighbour(s) has/have unknown elevation value(s). The outlet is the cell with the lowest elevation among those potential outlets. Once the outlet is determined, the LCP algorithm will start searching its neighbouring upslope cells along the least slope path. However, if a sink is encountered when searching uphill, the search will follow the steepest downhill slope to the bottom of the sink and then proceed again along the least steep uphill slope. The search proceeds until all grid cells are processed. For each search, the flow direction is estimated for each neighbouring cell of the current cell, towards the current cell if the neighbouring cell has the maximum descent to the current cell. One exception is when there is a sink; then the flow direction at the bottom of the sink is set to the outlet of the sink, i.e. the lowest cell along the boundary of the sink. In other words, water at the outlet of the sink cannot flow into the bottom of the sink.

The Triangular Form based Multiple flow algorithm (TFM) algorithm, one of the traditional hydrology-based algorithms, is capable of simulating the surface flow within a cell, and provides more accurate flow estimations than other commonly used flow routing algorithms due to its sensitivity to terrain forms (Pilesjö & Hasan, 2014). The approach is to sub-partition the grid cell into eight local, triangular facets between the cell centre and the eight surrounding cell centres of the neighbouring cells. Based on the aspect of each facet, water can be routed in three ways: First, to one or two neighbouring cells; secondly, only to one neighbouring facet; thirdly, to two neighbouring facets or to one neighbouring cell and one neighbouring facet. The algorithm is based on multiple flow distribution, allowing the flow out of each cell to more than one neighbouring cell.
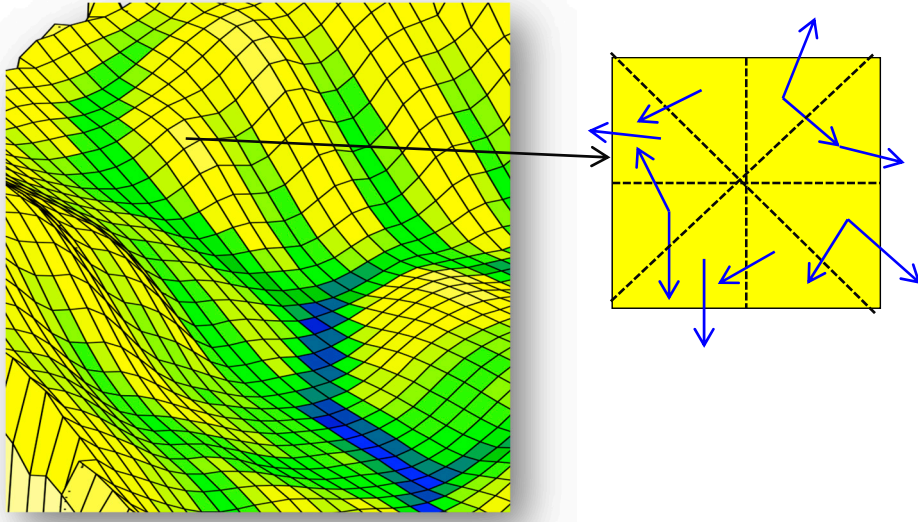
Figure 3.1. An example for flow direction determination by TFM algorithm

Due to the advantage of LCP algorithm and TFM algorithm, a combination of these two algorithms is proposed to solve the problems of traditional LCP implementations and the problems of sinks over DEMs. With the combined algorithm, there are two mains steps to determine drainage path: First, start from the outlet and record its upslope grid cell along the least cost path and then repeat the same procedure until the last grid cell is recorded. Reverse the order that grid cells are recorded, we can get a new order in which cells must be processed for flow distribution; secondly, following the new order, distribute the flow from each cell to its downstream cell(s) by implementing the TFM algorithm and at the same time accumulated flow for each grid cell is calculated. When there is an open sink, the flow from the bottom of the sink is distributed to the downstream outlet cell as mentioned above. Thereafter the drainage networks could be extracted with a threshold value of channel initiation based on the accumulated flow data.

3.2 Data-independent error assessment

A data-independent error assessment of grid-based flow routing algorithm by Zhou and Liu (2002) is used to quantitatively evaluate the combined algorithm. In this assessment method, four mathematical surfaces are generated for the simplification of the complexity of the real world surface, namely ellipsoid, inverse ellipsoid, saddle, and plane surfaces. Based on the four mathematical surfaces, several flow routing algorithms are applied to derive Specific Catchment Area (SCA) values. Comparing the derived SCA value with the theoretical true value for each cell, the errors generated by the selected algorithms can be computed and a statistical analysis of the errors can be carried out. The Root Mean Square Error (RMSE), Mean Error (ME), and Standard Deviation (SD) are applied to estimate the overall accuracy of the selected algorithms. The error at each cell is computed as shown in Eq. (3.1):

$$E_i = SCA_i - SCA_{t\_i} \tag{3.1}$$

where E_i denotes the error (or residual) at the given cell at the ith cell using a selected algorithm, SCA_i and $SCA_{i\text{-}i}$ denote the estimated and theoretical true values of SCA at the *ith* cell, respectively.

The SCA is defined as 'upslope area per unit width of contour' (Wilson & Gallant, 2000). The theoretical 'true' SCA value for each cell of the four mathematical surfaces has been computed in Zhou and Liu (2002). For grid-based elevation models, SCA is calculated according to Eq. (3.2)

$$SCA_i = \frac{TCA_i}{CL_i} \tag{3.2}$$

where TCA_i denotes total upslope area at *i*th cell, and CL_i denotes contour length towards the *i*th cell. TCA_i is computed as flow accumulation at the *i*th cell estimated from a selected flow routing algorithm multiplying the area of a grid cell.

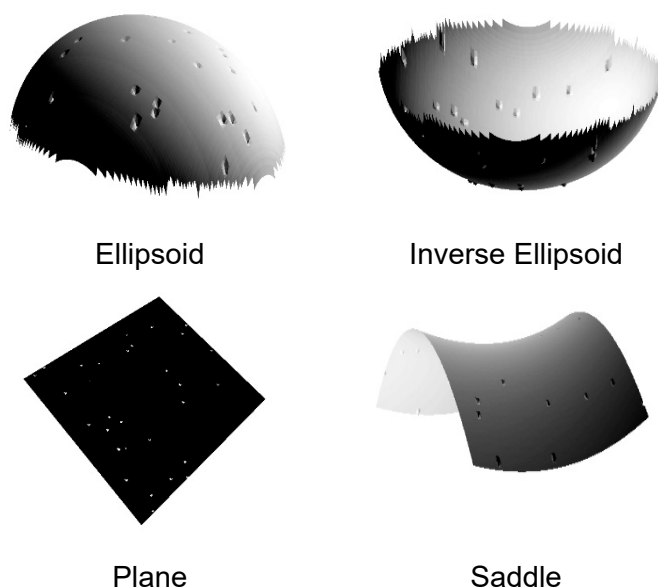|	
Ellipsoid	Inverse Ellipsoid
Plane	Saddle

Figure 3.2. Hill shade maps of the four new mathematical surfaces, with sun elevation angle of 45º and sun azimuth angle of 45º. 30 random sinks of size 4 (i.e. 4 grid cells at the bottom of each sink) are generated for each of the four new mathematical surfaces.

3.3 Uncertainty of drainage network delineation

As mentioned above, the uncertainty of drainage network delineation is not only related to topography but also linked to land cover, soil type, etc. In order to explore the relation between different environmental factors and the resulting drainage network, it is necessary to know at which scale the environmental factors should be investigated. As water moves down to the river mouth of a basin, upslope hydrological processes may, to some extent, impact the water downslope, but usually do not control the downslope processes since hydrological processes can vary greatly with changing land cover, soil texture, or terrain, as water flows down. Sometimes, the impact of upslope areas on downslope flow is very weak. For instance, there might be large and dense streams on upslope areas but these streams may be gone when reaching downslope areas due to rapid absorption of water by soils. Therefore, local factors are argued to be more important than upslope environmental factors in influencing the actual position of the drainage network.

In addition, to study the uncertainty of delineated draiange network, it is crucial to validate the delineation result against reference network. However, due to time constrains, it is usually impossible to map the whole drainage network in field. Instead, a limited number of field observations of stream network is an alternative as reference network. Thus, the

relation between environmental factors and delineated drainage network could be converted to the relations between local environmental conditions around field observations and the position accuracy of delineated drainage network at field observations. Local environmental conditions around field observations can be represented by the dominant environment conditions surrounding field observation within a window of representative size. Position accuracy of delineated drainage network at field observations is an average value for each group with the same dominant environmental condition, and can be calculated according to Eq. (3.3):

$$T = N_{fitted} / N_{total}$$

(3.3)

Where *T* indicates the position accuracy, *Nfitted* indicates the number of filed observations that are captured by the delineated drainage network, and *Ntotal* is the total number of field observations. In fact, the way to calculate the accuracy mentioned above is uncertain due to the uncertain threshold of contributing area for drainage network delineation and the definition of captured field observations by delineated network. Because of measurement errors of field observations, we define the field observations that are within an acceptable distance from delineated network as captured observations.

3.4 Catchment characterization

Catchment geomorphology, which evolves slowly over decades to millennia in response to climate, geology, hydrology and vegetation dynamics, imparts strong controls on contemporary hydrologic regimes (Beven et al., 1988; McGlynn & McDonnell, 2003; Woods, 2003). Basin structure through the basin order, order ratios (area ratio, bifurcation ratio, and length ratio) (Smart, 1972; Strahler, 1952), physical characteristics (slopes, soil type) and rainfall characteristics have been incorporated into a hydrologic response model to derive flood frequency curve (Hebson & Wood, 1982; Rodríguez-Iturbe & Valdes, 1979). In addition, the dynamics of runoff has been found highly related to the geomorphological structure of catchments (Beven et al., 1988).

DOC, transported from terrestrial to stream channels, driven by hydrologic flow, and the spatial and temporal variation of its concentration could be linked to stream order (Ågren et al., 2007; Temnerud & Bishop, 2005), travel time and pathways (Lyon et al., 2010), elevation (Fang et al., 2012), aspect and slope (Callaghan et al., 2013; Giesler et al., 2014), topographic wetness index (Musolff et al., 2018), and etc. To facilitate a more complete understanding of the DOC variability and its relationship to catchment geomorphology in (sub)arctic catchments, a systematic geospatial analysis of different catchment

geomorphological characteristics is performed.

3.5 Feature selection

3.5.1 Random forest approach

Random forest approach is used to select useful features from the morphometry factors that drives the distribution of DOC concentration. The random forest is a classification algorithm consisting of many decision trees. Each individual tree in the random forest spits out a class prediction and the class with the most votes becomes the model's prediction. The random forest uses bagging and feature randomness when building each individual tree to try to create an uncorrelated forest of trees whose prediction by committee is more accurate than that of any individual tree (Breiman, 2001) (Fig.3.4) The traditional decision tree can select from all features and pick the one that produces the most separation between observations in the left node versus those in the right node. In contrast, in the random forest, each individual tree is not only trained on different sets of data due to bagging but also use different features (random subsets of all features) to make decisions. Bagging process allows each individual tree to randomly sample from the original dataset with replacement, leading to significantly different tree structures. The size of training data for each individual tree is the same as the original data. Feature randomness forces even more variation amongst the trees in the model and ultimately results in lower correlation between trees and more diversification.

An illustrative dataset with two classes

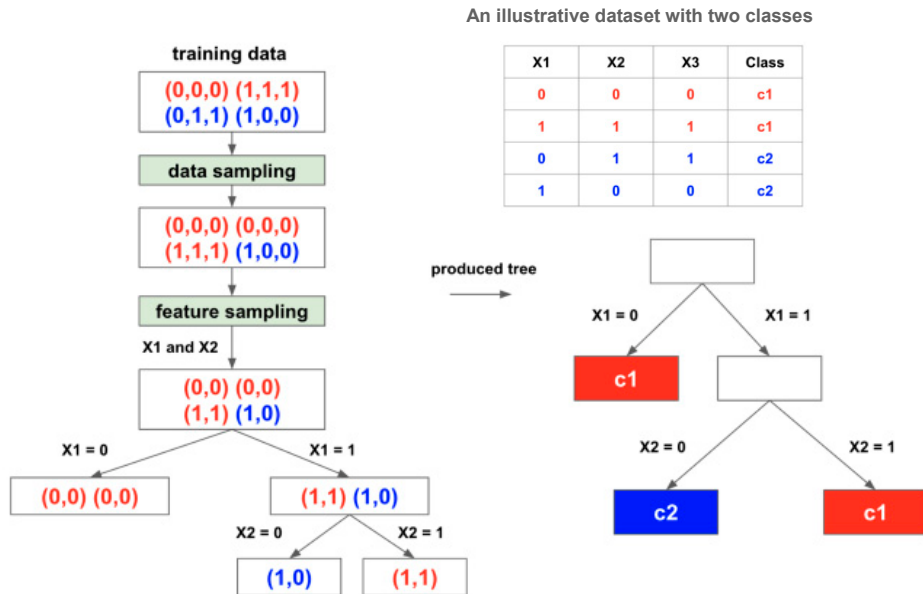| X1	X2	X3	Class
0	0	0	c1
1	1	1	c1
0	1	1	c2
1	0	0	c2

Figure 3.3. The process of building a random forest tree. Red texts indicate original dataset and blue texts are training dataset which has the same size as original dataset, but its value for each feature is randomly sampled from original dataset.
(Source: https://towardsdatascience.com/random-forest-3a55c3aca46d)

3.5.2 Principle Component Analysis

Principal component analysis is performed to find out the components that contains most information for the morphometry factors. Principal Component Analysis, or PCA, is a dimensionality-reduction method that is often used to transform a large set of variables into a smaller number that still contains most of the information in the large set (Hotelling, 1933). The main workflow of principal component analysis is to compute eigenvectors and eigenvalues of the covariance matrix for all possible pairs of the initial variables (values are standardized), construct principal components by ordering eigenvectors by their eigenvalues in descending order, and reorient the data from original axes to the ones represented by the principal components (Fig.3.5).
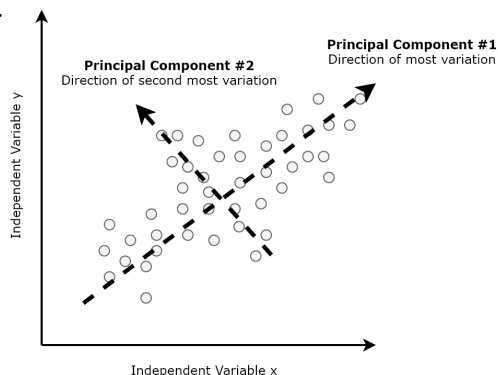

Figure 3.4. Principal components analysis
(Source:https://hackernoon.com/principal-component-analysis-unsupervised-learning-model-8f18c7683262)

3.6 LPJ-GUESS model

The Lund-Potsdam-Jena General Ecosystem Simulator (LPJ-GUESS model)(Smith et al., 2001; Smith et al., 2014) is used to simulate vegetation dynamics, e.g. vegetation contracture and composition in terms of plant functional types (PFTs), and ecosystem biogeochemistry. LPJ-GUESS is a dynamic global vegetation model (DGVM) which uniquely combines an individual-based and dynamic vegetation model accounting for plant physiology, and carbon pool dynamics with a land surface and hydrologic module. Like most of land models for hydrometerology, climate and carbon-cycle studies, LPJ-GUESS model assume a globally uniform value for the thickness of permeable layers, i.e. 1.5 m. To introduce groundwater, constant soil depth in the original version of LPJ-GUESS is updated with available global soil data (Pelletier et al., 2016). Water table depth data is obtained from Fan et al.(2013). The model is forced with changing CO_2,

nitrogen, climate and land use (Fig3.6). The model accounts for the emissions from land use change and carbon uptake due to regrowth after agricultural abandonment.
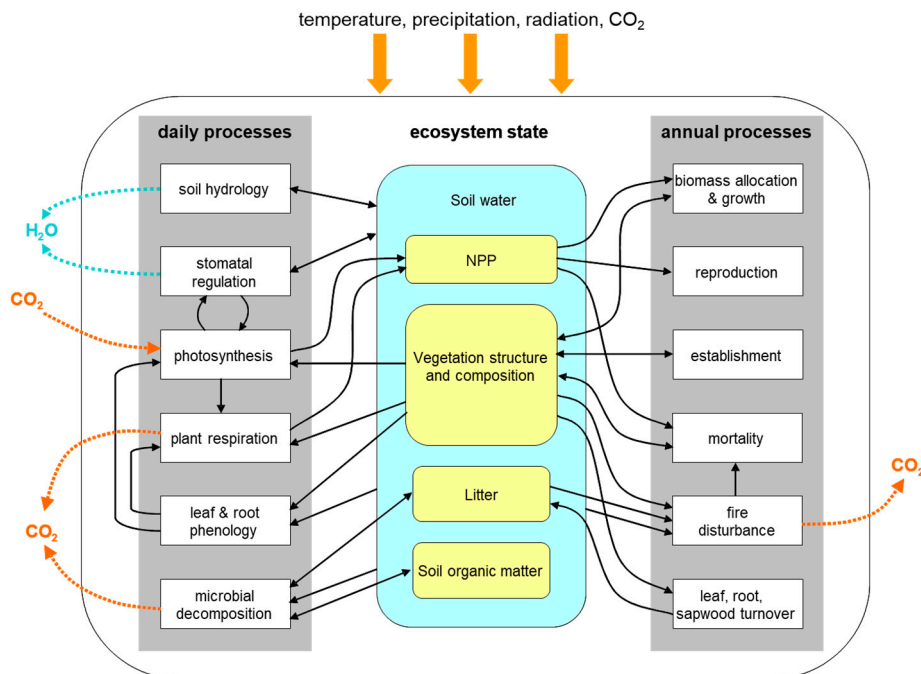

Figure 3.5. Conceptual representation of LPJ-GUESS model. The potential output of the model includes current ecosystem state variables (e.g. biomass for different plant functional types, PFTs, carbon and water fluxes exchange between atmosphere and ecosystems). Source:http://iis4.nateko.lu.se/lpj-guess/

LPJ-GUESS model assumes a globally uniform value for the thickness of soil layers, i.e. 1500 mm. In total there are two soil layers: the upper layer is of 500 mm and the lower layer is of 1000 mm. However, soil depth in the Amazon varies spatially and could be as deep as 20 m. Thus, we adjust the depth of the lower layer based on the soil data reported in (Pelletier et al., 2016) for each grid cell. If soil depth is less than 500 mm, soil depth is set to 500 mm and the lower layer is removed. This is to ensure the validity of soil evapotranspiration which occurs in the top 200 mm of the upper soil layer. Deep soil layers allow more water storage, and thus may improve the water stress conditions for plants. In addition, plant use of groundwater is assumed when water supply could not meet the transpiration demand.

References

Adams, J., & Chandler, J. (2002). Evaluation of LIDAR and medium scale photogrammetry for detecting soft-cliff coastal change. *The Photogrammetric Record, 17*(99), 405-418. doi:10.1111/0031-868X.00195

Ågren, A., Buffam, I., Jansson, M., & Laudon, H. (2007). Importance of seasonality and small streams for the landscape regulation of dissolved organic carbon export. *Journal of Geophysical Research: Biogeosciences, 112*(G3).

Ahlström, A., Canadell, J. G., Schurgers, G., Wu, M., Berry, J. A., Guan, K., & Jackson, R. B. (2017). Hydrologic resilience and Amazon productivity. *Nature communications, 8*(1), 387.

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., Yoo, K. (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment, 9*(1), 53-60.

Baker, I., Prihodko, L., Denning, A., Goulden, M., Miller, S., & Da Rocha, H. (2008). Seasonal drought stress in the Amazon: Reconciling models and observations. *Journal of Geophysical Research: Biogeosciences, 113*(G1).

Band, L. E. (1986). Topographic partition of watersheds with digital elevation models. *Water resources research, 22*(1), 15-24.

Barbeta, A., & Peñuelas, J. (2017). Relative contribution of groundwater to plant transpiration estimated with stable isotopes. *Scientific reports, 7*(1), 10580.

Battin, T. J., Luyssaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., & Tranvik, L. J. (2009). The boundless carbon cycle. *Nature Geoscience, 2*(9), 598.

Beven, K. J. (2011). *Rainfall-runoff modelling: the primer*: John Wiley & Sons.

Beven, K. J., Wood, E. F., & Sivapalan, M. (1988). On hydrological heterogeneity—catchment morphology and catchment response. *Journal of hydrology, 100*(1-3), 353-375.

Bhattacharya, A., & Michael, A. (2006). *Land drainage: principles, methods and applications*: Vikas Publishing House.

Bicknell, B. R., Imhoff, J. C., Kittle Jr, J. L., Jobes, T. H., Donigian Jr, A. S., & Johanson, R. (2001). Hydrological simulation program-Fortran: HSPF version 12 user's manual. *AQUA TERRA Consultants, Mountain View, California*.

Bracken, L., Wainwright, J., Ali, G., Tetzlaff, D., Smith, M., Reaney, S., & Roy, A. (2013). Concepts of hydrological connectivity: research approaches, pathways and future agendas. *Earth-Science Reviews, 119*, 17-34.

Brando, P. M., Goetz, S. J., Baccini, A., Nepstad, D. C., Beck, P. S., & Christman, M. C. (2010). Seasonal and interannual variability of climate and vegetation indices across the Amazon. *Proceedings of the National Academy of Sciences, 107*(33), 14685-14690.

Breiman, L. (2001). Random forests. *Machine learning, 45*(1), 5-32.

Buffam, I., Laudon, H., Temnerud, J., Mörth, C. M., & Bishop, K. (2007). Landscape-scale variability of acidity and dissolved organic carbon during spring flood in a boreal stream network. *Journal of Geophysical Research: Biogeosciences, 112*(G1).

Callaghan, T. V., Jonasson, C., Thierfelder, T., Yang, Z., Hedenås, H., Johansson, M. Olofsson, J. (2013). Ecosystem change and stability over multiple decades in the Swedish subarctic: complex processes and multiple drivers. *Philosophical Transactions of the Royal Society B: Biological Sciences, 368*(1624), 20120488.

Canham, C. D., Pace, M. L., Papaik, M. J., Primack, A. G., Roy, K. M., Maranger, R. J., Spada, D. M. (2004). A spatially explicit watershed-scale analysis of dissolved organic carbon in Adirondack lakes. *Ecological applications, 14*(3), 839-854.

Chaves, H., & Nearing, M. (1991). Uncertainty analysis of the WEPP soil erosion model. *Transactions of the ASAE, 34*(6), 2437-2444. doi:10.13031/2013.31890

Chen, D., & Chen, H. W. (2013). Using the Köppen classification to quantify climate variation and change: an example for 1901–2010. *Environmental Development, 6*, 69-79.

Christoffersen, B. O., Restrepo-Coupe, N., Arain, M. A., Baker, I. T., Cestaro, B. P., Ciais, P., . . . Gulden, L. (2014). Mechanisms of water supply and vegetation demand govern the seasonality and magnitude of evapotranspiration in Amazonia and Cerrado. *Agricultural and forest meteorology, 191*, 33-50.

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Middelburg, J. J. (2007). Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. *Ecosystems, 10*(1), 172-185.

Cory, R. M., Ward, C. P., Crump, B. C., & Kling, G. W. (2014). Sunlight controls water column processing of carbon in arctic fresh waters. *Science, 345*(6199), 925-928.

Dietrich, W. E., Wilson, C. J., Montgomery, D. R., McKean, J., & Bauer, R. (1992). Erosion thresholds and land surface morphology. *Geology, 20*(8), 675-679. doi:10.1130/0091-7613(1992)020<0675:ETALSM>2.3.CO;2

Evans, C. D., & Thomas, D. N. (2016). Controls on the processing and fate of terrestrially-derived organic carbon in aquatic ecosystems: synthesis of special issue. In: Springer.

Fan, Y., & Miguez-Macho, G. (2010). Potential groundwater contribution to Amazon evapotranspiration. *Hydrology and Earth System Sciences, 14*(10), 2039-2056.

Fang, X., Xue, Z., Li, B., & An, S. (2012). Soil organic carbon distribution in relation to land use and its storage in a small watershed of the Loess Plateau, China. *Catena, 88*(1), 6-13.

Findlay, S. (1995). Importance of surface-subsurface exchange in stream ecosystems: The hyporheic zone. *Limnology and oceanography, 40*(1), 159-164.

Freeman, T. G. (1991). Calculating catchment area with divergent flow based on a regular grid. *Computers & Geosciences, 17*(3), 413-422. doi:10.1016/0098-3004(91)90048-I

Gallant, J. C., & Hutchinson, M. F. (2011). A differential equation for specific catchment area. *Water resources research, 47*(5). doi:10.1029/2009WR008540

Giesler, R., Lyon, S. W., Morth, C., Karlsson, J., Karlsson, E., Jantze, E. J., Humborg, C. (2014). Catchment-scale dissolved carbon concentrations and export estimates across six subarctic streams in northern Sweden. *Biogeosciences, 11*(2), 525-537.

Good, S. P., Noone, D., & Bowen, G. (2015). Hydrologic connectivity constrains partitioning of global terrestrial water fluxes. *Science, 349*(6244), 175-177.

Graneli, W. (2012). Brownification of lakes. *Encyclopedia of lakes and reservoirs*, 117-119.

Greysukh, V. (1967). The possibility of studying landforms by means of digital computers. *Soviet Geography, 8*(3), 137-149.

Hart, P. E., Nilsson, N. J., & Raphael, B. (1968). A formal basis for the heuristic determination of minimum cost paths. *IEEE transactions on Systems Science and Cybernetics, 4*(2), 100-107. doi:10.1109/TSSC.1968.300136

Haxeltine, A., & Prentice, I. C. (1996). BIOME3: An equilibrium terrestrial biosphere model based on ecophysiological constraints, resource availability, and competition among plant functional types. *Global Biogeochemical Cycles, 10*(4), 693-709.

Hebson, C., & Wood, E. F. (1982). A derived flood frequency distribution using Horton order ratios. *Water Resources Research, 18*(5), 1509-1518.

Heine, R. A., Lant, C. L., & Sengupta, R. R. (2004). Development and comparison of approaches for automated mapping of stream channel networks. *Annals of the Association of American Geographers, 94*(3), 477-490.

Hodgson, M. E., Jensen, J., Raber, G., Tullis, J., Davis, B. A., Thompson, G., & Schuckman, K. (2005). An evaluation of lidar-derived elevation and terrain slope in leaf-off conditions. *Photogrammetric Engineering & Remote Sensing, 71*(7), 817-823. doi:10.14358/PERS.71.7.817

Holmgren, P. (1994). Multiple flow direction algorithms for runoff modelling in grid based elevation models: an empirical evaluation. *Hydrological Processes, 8*(4), 327-334. doi:10.1002/hyp.3360080405

Hotchkiss, E., Hall Jr, R., Sponseller, R., Butman, D., Klaminder, J., Laudon, H. Karlsson, J. (2015). Sources of and processes controlling CO_2 emissions change with the size of streams and rivers. *Nature Geoscience, 8*(9), 696.

Hotelling, H. (1933). Analysis of a complex of statistical variables into principal components. *Journal of educational psychology, 24*(6), 417.

Huete, A. R., Didan, K., Shimabukuro, Y. E., Ratana, P., Saleska, S. R., Hutyra, L. R., Myneni, R. (2006). Amazon rainforests green-up with sunlight in dry season. *Geophysical research letters, 33*(6).

Hutchinson, M. (1989). A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. *Journal of Hydrology, 106*(3-4), 211-232. doi:10.1016/0022-1694(89)90073-5

Ibbitt, R. P., Willgoose, G. R., & Duncan, M. J. (1999). Channel network simulation models compared with data from the Ashley River, New Zealand. *Water resources research, 35*(12), 3875-3890.

Jantze, E. J., Laudon, H., Dahlke, H. E., & Lyon, S. W. (2015). Spatial variability of dissolved organic and inorganic carbon in subarctic headwater streams. *Arctic, antarctic, and alpine research, 47*(3), 529-546.

Jenson, S. K., & Domingue, J. O. (1988). Extracting topographic structure from digital elevation data for geographic information system analysis. *Photogrammetric engineering and remote sensing, 54*(11), 1593-1600.

Johnston, D., & Timlin, D. (2000). *Spatial data accuracy and quality assessment for environmental management.* Paper presented at the Proceedings of the 4th International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences.

Jonsson, M., Hedström, P., Stenroth, K., Hotchkiss, E. R., Vasconcelos, F. R., Karlsson, J., & Byström, P. (2015). Climate change modifies the size structure of assemblages of emerging aquatic insects. *Freshwater Biology, 60*(1), 78-88.

Karásek, P., Tlapáková, L., & Podhrázská, J. (2015). The Location and Extent of Systematic Drainage in Relation to Land Use in the Past and at Present and in Relation to Soil Vulnerability to Accelerater Infiltration in the Protected Landscape Area Železné Hory. *Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, 63*(4), 1121-1131. doi:10.11118/actaun201563041121

Kinner, D., Mitasova, H., Harmon, R., Toma, L., & Stallard, R. (2005). GIS-based stream network analysis for the Chagres River Basin, Republic of Panama. *The Rio Chagres: A Multidisciplinary Profile of a Tropical Watershed, Springer/Kluwer*, 83-95.

Lai, Z., Li, S., Lv, G., Pan, Z., & Fei, G. (2016). Watershed delineation using hydrographic features and a DEM in plain river network region. *Hydrological Processes, 30*(2), 276-288. doi:10.1002/hyp.10612

Lauerwald, R., Laruelle, G. G., Hartmann, J., Ciais, P., & Regnier, P. A. (2015). Spatial patterns in CO2 evasion from the global river network. *Global Biogeochemical Cycles, 29*(5), 534-554.

Li, M., Peng, C., Wang, M., Xue, W., Zhang, K., Wang, K., Zhu, Q. (2017). The carbon flux of global rivers: A re-evaluation of amount and spatial patterns. *Ecological Indicators, 80*, 40-51.

Lindsay, J. B. (2015). Efficient hybrid breaching-filling sink removal methods for flow path enforcement in digital elevation models. *Hydrological Processes.* doi:10.1002/hyp.10648

Lindsay, J. B., & Creed, I. F. (2005). Removal of artifact depressions from digital elevation models: towards a minimum impact approach. *Hydrological Processes, 19*(16), 3113-3126. doi:10.1002/hyp.5835

Liu, Y. Y., van Dijk, A. I., Miralles, D. G., McCabe, M. F., Evans, J. P., de Jeu, R. A., Wang, L. (2018). Enhanced canopy growth precedes senescence in 2005 and 2010 Amazonian droughts. *Remote Sensing of Environment, 211*, 26-37.

Luizão, R. C., Luizão, F. J., Paiva, R. Q., Monteiro, T. F., Sousa, L. S., & Kruijt, B. (2004). Variation of carbon and nitrogen cycling processes along a topographic gradient in a central Amazonian forest. *Global Change Biology, 10*(5), 592-600.

Lyon, S., Mörth, M., Humborg, C., Giesler, R., & Destouni, G. (2010). The relationship between subsurface hydrology and dissolved carbon fluxes for a sub-arctic catchment. *Hydrology and Earth System Sciences, 14*(6), 941-950.

Malhi, Y., Aragão, L. E., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., Meir, P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences, 106*(49), 20610-20615.

Manoli, G., Ivanov, V. Y., & Fatichi, S. (2018). Dry-season greening and water stress in Amazonia: The role of modeling leaf phenology. *Journal of Geophysical Research: Biogeosciences, 123*(6), 1909-1926.

Martz, L. W., & De Jong, E. (1988). CATCH: a FORTRAN program for measuring catchment area from digital elevation models. *Computers & Geosciences, 14*(5), 627-640. doi:10.1016/0098-3004(88)90018-0

Martz, L. W., & Garbrecht, J. (1999). An outlet breaching algorithm for the treatment of closed depressions in a raster DEM. *Computers & Geosciences, 25*(7), 835-844. doi:10.1016/S0098-3004(99)00018-7

Matsui, T., Yagihashi, T., Nakaya, T., Taoda, H., Yoshinaga, S., Daimaru, H., & Tanaka, N. (2004). Probability distributions, vulnerability and sensitivity in Fagus crenata forests following predicted climate changes in Japan. *Journal of Vegetation Science, 15*(5), 605-614.

McGlynn, B. L., & McDonnell, J. J. (2003). Role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. *Water Resources Research, 39*(4).

Meehl, G. A., Stocker, T. F., Collins, W. D., Friedlingstein, P., Gaye, T., Gregory, J. M., Noda, A. (2007). Global climate projections.

Metz, M., Mitasova, H., & Harmon, R. (2011a). *Efficient extraction of drainage networks from massive, radar-based elevation models with least cost path search*. Retrieved from

Metz, M., Mitasova, H., & Harmon, R. (2011b). Efficient extraction of drainage networks from massive, radar-based elevation models with least cost path search. *Hydrology and Earth System Sciences, 15*(2), 667. doi:10.5194/hess-15-667-2011

Molle, F., Wester, P., Hirsch, P., Jensen, J. R., Murray-Rust, H., Paranjpye, V., Van der Zaag, P. (2007). *River basin development and management*. Retrieved from

Montgomery, D. R., & Dietrich, W. E. (1992). Channel initiation and the problem of landscape scale. *Science, 255*(5046), 826-830. doi:10.1126/science.255.5046.826

Musolff, A., Fleckenstein, J., Opitz, M., Büttner, O., Kumar, R., & Tittel, J. (2018). Spatio-temporal controls of dissolved organic carbon stream water concentrations. *Journal of hydrology, 566*, 205-215.

Myneni, R. B., Yang, W., Nemani, R. R., Huete, A. R., Dickinson, R. E., Knyazikhin, Y., Saatchi, S. S. (2007). Large seasonal swings in leaf area of Amazon rainforests. *Proceedings of the National Academy of Sciences, 104*(12), 4820-4823.

Neitsch, S. L., Arnold, J. G., Kiniry, J. R., & Williams, J. R. (2011). *Soil and water assessment tool theoretical documentation version 2009*. Retrieved from

O'Callaghan, J. F., & Mark, D. M. (1984). The extraction of drainage networks from digital elevation data. *Computer vision, graphics, and image processing, 28*(3), 323-344. doi:10.1016/S0734-189X(84)80011-0

Olefeldt, D., Roulet, N., Giesler, R., & Persson, A. (2013). Total waterborne carbon export and DOC composition from ten nested subarctic peatland catchments—importance of peatland cover, groundwater influence, and inter-annual variability of precipitation patterns. *Hydrological Processes, 27*(16), 2280-2294.

Orlandini, S., Moretti, G., Franchini, M., Aldighieri, B., & Testa, B. (2003). Path-based methods for the determination of nondispersive drainage directions in grid-based digital elevation models. *Water resources research, 39*(6).

Passalacqua, P., Do Trung, T., Foufoula-Georgiou, E., Sapiro, G., & Dietrich, W. E. (2010). A geometric framework for channel network extraction from lidar: Nonlinear diffusion and geodesic paths. *Journal of Geophysical Research: Earth Surface, 115*(F1).

Pelletier, J. D., Broxton, P. D., Hazenberg, P., Zeng, X., Troch, P. A., Niu, G. Y., Gochis, D. (2016). A gridded global data set of soil, intact regolith, and sedimentary deposit thicknesses for regional and global land surface modeling. *Journal of Advances in Modeling Earth Systems, 8*(1), 41-65.

Peucker, T. K., & Douglas, D. H. (1975). Detection of surface-specific points by local parallel processing of discrete terrain elevation data. *Computer Graphics and image processing, 4*(4), 375-387. doi:10.1016/0146-664X(75)90005-2

Phillips, O. L., Aragão, L. E., Lewis, S. L., Fisher, J. B., Lloyd, J., López-González, G., Quesada, C. A. (2009). Drought sensitivity of the Amazon rainforest. *Science, 323*(5919), 1344-1347.

Pilesjö, P., & Hasan, A. (2014). A Triangular Form-based Multiple Flow Algorithm to Estimate Overland Flow Distribution and Accumulation on a Digital Elevation Model. *Transactions in GIS, 18*(1), 108-124. doi:10.1111/tgis.12015

Pirotti, F., & Tarolli, P. (2010). Suitability of LiDAR point density and derived landform curvature maps for channel network extraction. *Hydrological Processes, 24*(9), 1187-1197. doi:10.1002/hyp.7582

Poulter, B., Heyder, U., & Cramer, W. (2009). Modeling the sensitivity of the seasonal cycle of GPP to dynamic LAI and soil depths in tropical rainforests. *Ecosystems, 12*(4), 517-533.

Quinn, P., Beven, K., Chevallier, P., & Planchon, O. (1991). The prediction of hillslope flow paths for distributed hydrological modelling using digital terrain models. *Hydrological Processes, 5*(1), 59-79.

Raymond, P. A., Bauer, J. E., Caraco, N. F., Cole, J. J., Longworth, B., & Petsch, S. T. (2004). Controls on the variability of organic matter and dissolved inorganic carbon ages in northeast US rivers. *Marine Chemistry, 92*(1-4), 353-366.

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Andersson, A. J. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience, 6*(8), 597.

Rieger, W. (1998). A phenomenon-based approach to upslope contributing area and depressions in DEMs. *Hydrological Processes, 12*(6), 857-872.

Rodríguez-Iturbe, I., & Rinaldo, A. (2001). *Fractal river basins: chance and self-organization*: Cambridge University Press.

Rodríguez-Iturbe, I., & Valdes, J. B. (1979). The geomorphologic structure of hydrologic response. *Water Resources Research, 15*(6), 1409-1420.

Saleska, S. R., Didan, K., Huete, A. R., & Da Rocha, H. R. (2007). Amazon forests green-up during 2005 drought. *Science, 318*(5850), 612-612.

Saleska, S. R., Wu, J., Guan, K., Araujo, A. C., Huete, A., Nobre, A. D., & Restrepo-Coupe, N. (2016). Dry-season greening of Amazon forests. *Nature, 531*(7594), E4.

Schneider, A., Jost, A., Coulon, C., Silvestre, M., Théry, S., & Ducharne, A. (2017). Global-scale river network extraction based on high-resolution topography and constrained by lithology, climate, slope, and observed drainage density. *Geophysical research letters, 44*(6), 2773-2781.

Sedell, J., Sharpe, M., Apple, D. D., Copenhagen, M., & Furniss, M. (2000). Water and the forest service. *FS Publication*.

Smart, J. (1972). Channel networks. *Advances in hydroscience, 8*, 305-346.

Smith, B., Prentice, I. C., & Sykes, M. T. (2001). Representation of vegetation dynamics in the modelling of terrestrial ecosystems: comparing two contrasting approaches within European climate space. *Global Ecology and Biogeography, 10*(6), 621-637.

Smith, B., Warlind, D., Arneth, A., Hickler, T., Leadley, P., Siltberg, J., & Zaehle, S. (2014). Implications of incorporating N cycling and N limitations on primary production in an individual-based dynamic vegetation model. *Biogeosciences, 11*, 2027-2054.

Sofia, G., Tarolli, P., Cazorzi, F., & Dalla Fontana, G. (2011). An objective approach for feature extraction: distribution analysis and statistical descriptors for scale choice and channel network identification. *Hydrology and Earth System Sciences, 15*(5), 1387.

Strahler, A. N. (1952). Hypsometric (area-altitude) analysis of erosional topography. *Geological Society of America Bulletin, 63*(11), 1117-1142.

Tang, J., Yurova, A. Y., Schurgers, G., Miller, P. A., Olin, S., Smith, B., Poska, A. (2018). Drivers of dissolved organic carbon export in a subarctic catchment: Importance of microbial decomposition, sorption-desorption, peatland and lateral flow. *Science of the Total Environment, 622*, 260-274.

Tarboton, D. G. (1997). A new method for the determination of flow directions and upslope areas in grid digital elevation models. *Water resources research, 33*(2), 309-319.

Temnerud, J., & Bishop, K. (2005). Spatial variation of streamwater chemistry in two Swedish boreal catchments: Implications for environmental assessment. *Environmental science & technology, 39*(6), 1463-1469.

Thommeret, N., Bailly, J.-S., & Puech, C. (2010). Extraction of thalweg networks from DTMs: application to badlands. *Hydrology and earth system sciences, 14*(8), 1527-1536.

Tiwari, T., Laudon, H., Beven, K., & Ågren, A. M. (2014). Downstream changes in DOC: Inferring contributions in the face of model uncertainties. *Water Resources Research, 50*(1), 514-525.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., . . . Knoll, L. B. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and oceanography, 54*(6part2), 2298-2314.

Tribe, A. (1992). Automated recognition of valley lines and drainage networks from grid digital elevation models: a review and a new method. *Journal of Hydrology, 139*(1-4), 263-293. doi:10.1016/0022-1694(92)90206-B

Turcotte, R., Fortin, J.-P., Rousseau, A., Massicotte, S., & Villeneuve, J.-P. (2001). Determination of the drainage structure of a watershed using a digital elevation model and a digital river and lake network. *Journal of Hydrology, 240*(3), 225-242. doi:10.1016/S0022-1694(00)00342-5

Veihmeyer, F., & Hendrickson, A. (1931). The moisture equivalent as a measure of the field capacity of soils. *Soil Science, 32*(3), 181-194.

Wang, L., & Liu, H. (2006). An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. *International journal of geographical information science, 20*(2), 193-213. doi:10.1080/13658810500433453

Wang, T. (2014). A New Algorithm for Extracting Drainage Networks from Gridded DEMs. In *Cartography from Pole to Pole* (pp. 335-353): Springer.

Wilson, J. P., & Gallant, J. C. (2000). Digital terrain analysis. *Terrain analysis: Principles and applications, 6*(12), 1-27.

Woods, R. (2003). The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics. *Advances in Water Resources, 26*(3), 295-309.

Wu, J., Albert, L. P., Lopes, A. P., Restrepo-Coupe, N., Hayek, M., Wiedemann, K. T., Prohaska, N. (2016). Leaf development and demography explain photosynthetic seasonality in Amazon evergreen forests. *Science, 351*(6276), 972-976.

Wu, M., Shi, P., Chen, A., Shen, C., & Wang, P. (2017). Impacts of DEM resolution and area threshold value uncertainty on the drainage network derived using SWAT. *Water SA, 43*(3), 450-462.

Würth, M., Winter, K., & Körner, C. (1998). In situ responses to elevated CO2 in tropical forest understorey plants. *Functional Ecology, 12*(6), 886-895.

Xiong, L., Tang, G., Yan, S., Zhu, S., & Sun, Y. (2014). Landform-oriented flow-routing algorithm for the dual-structure loess terrain based on digital elevation models. *Hydrological Processes, 28*(4), 1756-1766. doi:10.1002/hyp.9719

Yamazaki, D., Baugh, C. A., Bates, P. D., Kanae, S., Alsdorf, D. E., & Oki, T. (2012). Adjustment of a spaceborne DEM for use in floodplain hydrodynamic modeling. *Journal of Hydrology, 436*, 81-91. doi:10.1016/j.jhydrol.2012.02.045

Yoeli, P. (1984). Computer-assisted determination of the valley and ridge lines of digital terrain models. *International Yearbook of Cartography, 24*, 197-206.

Young, R., Smart, G., & Harding, J. (2004). Impacts of hydro-dams, irrigation schemes and river control works. *Freshwaters of New Zealand*, 37.31-37.15.

Zhou, Q., & Liu, X. (2002). Error assessment of grid-based flow routing algorithms used in hydrological models. *International Journal of Geographical Information Science, 16*(8), 819-842.

Zhou, Q., Pilesjö, P., & Chen, Y. (2011). Estimating surface flow paths on a digital elevation model using a triangular facet network. *Water resources research, 47*(7). doi:10.1029/2010WR009961