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Summary of the Doctoral thesis

Hydrological processes and dynamics in the changing climate and environment: Lessons learned from multiple temporal and spatial scales

Hydrologické procesy a jejich dynamika v měnícím se klimatu a prostředí: Zkušenosti z výzkumu na různých časových a prostorových škálách

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ABSTRACT

Climate change, along with the changes in land use and land cover (LULC), is the key factor driving the changes in hydrological processes and dynamics in a basin. This thesis emphasized on understanding the impact of both long-term climate change and abrupt anthropogenic driven agricultural intensification or natural driven insect-induced forest disturbance on hydrological processes and dynamics at varying spatial and temporal scales in two diverting terrestrial environment.

Two pattern-based investigations, one case study in a forest region in Central Europe and another in a semi-arid region in Central Asia, were aimed to answer the main research question "*what are the responses of hydrological dynamics and the related hydro-geochemical conditions to climate change and certain changes in LULC at a basin-scale?*". The long-term hydro-climatic dataset was used for conducting statistical analyses and establishing hydro-climatic modelling at the basin scale. We further conducted process-based studies, attempting to understand how and why the specific hydrological dynamics were altered at smaller spatial and temporal scales: (i) a catchment-scale tracer-based experiment was conducted to examine multi-timescales changes in subsurface chemical composition and in runoff generation processes after bark beetle infestation; (ii) a soil column-scale theoretical analysis was studied to address the importance of velocity-celerity difference in studying tracer transport; (iii) two plot-scale model-based evapotranspiration estimations in a Soil-Vegetation-Atmosphere-Transfer (SVAT) model scheme were conducted to offer an alternative to better understand evaporation from soil, transpiration, and evaporation from canopy; and (iv) a plot-scale sap flow experiment was designed to estimate the canopy conductance during the vegetation period of beech forest.

Two pattern-based case studies pointed out the significant hydrological responses to the warmer climate under different environment, in the studied mid-latitude Central Europe Mountain the runoff seasonality shifted in terms of total runoff share, occurrence of peak flows and low flows, while Central Asia experienced a decrease in river flow and significant changes in riverine nitrogen concentrations. The processes-based studies highlighted that complex hydrological processes including streamflow, subsurface flow, geochemical conditions, and evapotranspiration are actively interacting with the changes in climate and LULC. In the experimental catchments of Central Europe undergone climate-induced bark beetle infestation, the geochemical changes, showing as an increased annual mean in-stream electrical conductivity (EC), are profound in the disturbed catchments were rapid after extensive infestation and last long over decades. The old water with substances of nitrogen and carbon released by dead trees was mixing with the rainwater in the rainfall-runoff events, and the shifts in EC-discharge hysteresis loops at each event implied changes in the subsurface chemical composition and runoff generation process. Such tracer-related studies require deep understanding in subsurface flow, we, therefore, proposed a celerity function that has been theoretically proved the usefulness when assists in studying the runoff behaviours and tracer transport.

Furthermore, evapotranspiration in the forested region is a key domain in the hydrological cycle. The newly developed SVAT model was applied in two different environments (i.e., forest and maize) where had full sets of dataset for validating the model, and the performance was better due to the more detailed description of energy transfer and the formation of advective soil vapour transport. One step forward, the results from sap flow experiment tracked the transpiration process in the beech forest, based on which the reversely-calculated canopy conductance was given to address the importance of knowing the site/species-specific canopy conductance for an area, which assists better understanding the transpiration process in newly formed beech stands after bark beetle outbreak in Central Europe.

Key words: hydrological processes, runoff, climate change, agricultural intensification, forest disturbance, geochemical transformation, celerity, evapotranspiration, SVAT model, sap flow, stomatal conductance

ABSTRAKT

Změna klimatu představuje společně se změnami ve využívání a struktuře krajinného krytu (LULC) klíčové faktory, ovlivňující změny v hydrologických procesech a jejich dynamice v povodí. Tato práce se zaměřila na pochopení dopadu dlouhodobých změn klimatu i rychlých změn struktury krajiny, vyvolané různými faktory, např. intenzifikací zemědělství nebo disturbancí lesa. Tyto procesy jsou zkoumány na různých prostorových a časových škálách a v odlišných přírodních prostředích.

Klíčovou výzkumnou otázkou, provazující jednotlivé případové studie je - "*jaká je reakce odtoku a související dynamiky hydrologických procesů na změny klimatu a změny LULC v povodí?*". Výzkum je realizovaný ve dvou typech prostředí - na příkladu lesních horských povodí ve střední Evropě a dále povodí v semiaridních oblastech Střední Asie.

Na prostorové úrovni uceleného povodí je výzkum založen na dlouhodobých hydroklimatických datech, využitých pro statistické analýzy a hydro-klimatické modelování. K pochopení příčin a dynamiky změn hydrologických procesů v menších prostorových a časových měřítcích byly prováděny následující studie, studující podrobně mechaniku hydrologickýách procesy v malých povodích: (i) na úrovni experimentálního malého povodí byl proveden experiment, využívající detekci změn v chemickém složení a dynamice generování odtoku po kůrovcové disturbanci pomocí hydrochemických stopovačů (tracerů); (ii) byla studována dynamika procesů v půdním prostředí; (iii) byly provedeny simulace evapotranspirace v experimentální povodí pomocí modelu Soil-Vegetation-Atmosphere-Transfer (SVAT), které nabídly alternativu k lepšímu pochopení odpařování z půdy, transpirace a odpařování z vegetace; a (iv) experiment efektu transpirace bukového lesa během vegetačního období pomocí měřením intenzity mízního toku.

Případové studie v prostředí středoevropského horského lesního povodí, poukázaly na významnou hydrologickou odezvu na oteplování klimatu, konkrétně na posuny v sezonalitě odtoku i frekvenci nebo extremitě výskytu vysokých a nízkých vodních stavů. V prostředí Střední Asie byly v reakci na změny prostředí zaznamenány poklesy odtoku, ale i významné změny v koncentracích dusíku. Detailní studie procesů pak potvrdily, že jednotlivé složky hydrologických procesů, zahrnující povrchové a podpovrchového proudění, geochemické podmínky nebo evapotranspiraci citlivě interagují na změny klimatu a LULC. V experimentálních povodích střední Evropy, kde došlo k rozsáhlé disturbanci lesa po kůrovcové kalamitě a působení změn klimatu, jsou geochemické změny, vyjádřené např. prostřednictvím ukazatele elektrické konduktivity (EC), rychlé, hluboké a dlouho trvající. K výrazným změnám dochází na úrovni dynamiky jednotlivých odtokových událostí, kdy se mění poměr mezi různými zdroji vodnosti s odlišnými hydrochemickými vlastnostmi, konkrétně zásob staré vody v povodí, obsahující vysoké koncentrace dusíku a uhlíku oproti vodě z aktuální srážkové události. Proměňující se geochemické poměry v povodí se odrážejí na průběhu hysterezních smyček koncentrací EC při odtokových událostech. Studie, využívající hydrochemické tracery vyžadují hluboké porozumění podpovrchovému proudění a proto jsme zde studovali a navrhli metodu výpočtu rychlostních funkcí proudění.

V lesních povodích je klíčovým prvkem hydrologického cyklu evapotranspirace. Nově vyvinutý SVAT model byl aplikován ve dvou odlišných prostředích - lesní a zemědělské plochy, pro které byly k dispozici podrobné řady dat pro validaci modelu. Jako podstatný krok pro zpěřesnění modelování evapotranspirace byl realizován instrumentálního monitoring mízního toku. Na jeho základě byla zpřesněna hodnota transpirace a její dynamiky v bukových porostech, nově se etablujících na plochách postižených disturbancí po kůrovcové kalamitě horského lesa.

Klíčová slova: hydrolotické procesy, dynamika odtoku, změna klimatu, intenzifikace zemědělství, disturbance lesa, geochemická transformace, evapotranspirace, SVAT model, mízní tok, monitoring.

1. Introduction

Climate change has a range of consequences, including the changes in water vapour, precipitation, and evapotranspiration rates, which could further impact hydrological processes (IPCC, 2013). Basin-scale studies under varying regional environment found that the hydrologic cycle in mid- to high-latitude snow-dominated mountainous regions (Barnett *et al.*, 2005), and in arid and semi-arid regions (Lioubimtseva and Henebry, 2009; Jarsjö, 2012; Sorg *et al.*, 2012) was expected to be more vulnerable and sensitive to climate change.

Moreover, land use and land cover (LULC) change is considered as another key factor driving the changes in hydrological processes and dynamics at the basin-scale, which could, in turn, contribute to local and regional climate change as well as to global climate warming (Houghton, 1999; Pielke, 2005). Feddema *et al.* (2005) highlighted the future LULC will most likely continue to be an important influence on climate for the next century, which emphasised the importance of new insights on considering the impacts of climate change and LULC on the hydrological system as a whole. Additionally, the changes in LULC include natural landscape transitions or anthropogenic changes, and many studies (Birsan *et al.*, 2005; Ma *et al.*, 2010; Ahmad *et al.*, 2012) pointed out both long-term and abrupt changes may result in significant runoff regime shifts, especially in response to extreme events, e.g., floods and droughts. Understanding the impacts of such changes requires profound knowledge into hydrological processes and dynamics across in time and space.

This thesis, therefore, examined the hydrological processes and dynamics under different environment at varying spatial and temporal scales. Among the terrestrial environment, two types of LULC change were studied. The study regions have diverting environmental problems but sharing one joint driver – climate change, which could lead to additional changes in multiple elements of hydrological system. Forest in the montane environment with coniferous forests and boreal forests is vulnerable to the increasingly warmer and drier climate (Seidl *et al.*, 2017), therefore, forest disturbance would pose as one of the most significant drivers for land cover changes. In particular, the insect induced infestation could still alter the land cover as consequences of climate change as the growth of beetle populations respond to the shifts in thermal condition and water stress (Bentz *et al.*, 2010; Anderegg *et al.*, 2013). Apart from the natural processes, agricultural intensification in the semi-arid area where has a large-scaled irrigation system is convinced to be highly sensitive to future climate change (Jarsjö *et al.*, 2012), and such land-use practices is one of the key anthropogenic land-use processes influencing the regional environment.

The hydrological system is, however, heterogeneous at all scale, attributing to the spatial or temporal variations in soil hydraulic properties (Zhao *et al.*, 1995; Geris *et al.*, 2014), topography (McGuire *et al.*, 2005), and land use (Bachmair and Weiler, 2012; Muñoz-Villers and McDonnell, 2013). We believe that quantifying and modelling such complex responses of a catchment require better understanding of the runoff sources, flow paths, and transit time distributions, which often employed tracer techniques (Burns *et al.*, 2001; Tetzlaff *et al.*, 2014). Using a tracer is based on the difference between new water (i.e., precipitation water) and old water (i.e., the water stored in the catchment prior to a hydrologic event) (Buttle, 1994; Laudon and Slaymaker, 1997; Weiler *et al.*, 2003), and solute transport behaviours are complex due to the pore water velocity distribution in the subsurface flow system (Beven and Germann, 1982). The pore water velocity distribution has been captured either by an experimentally-obtained breakthrough curve (Brusseau and Rao, 1990) or by natural or artificial tracers in a hydrological system (Köhne *et al.*, 2009). Therefore, new theoretical analysis is needed for better understanding the implications of the tracers in hydrological studies and how to accurately interpret tracer transport together with water flow.

Hydrological models are widely used for conceptualizing the real system, which could be further used for predicting and evaluating the possible changes of runoff, water resources, water quality, nutrient circulation, sediment or tracer transport, LULC, climate change, etc. (Devia *et al.*, 2015). The current physical-based hydrological model focuses on describing the water cycle in a hillslope/catchment, which often estimates the evapotranspiration (ET) based on long-term measurements with a standard Penman-Monteith equation (Allen *et al.*, 1998) or a Shuttleworth-Wallace equation (Zhou *et al.*, 2006; Ridler *et al.*, 2014). Therefore, for better description of ET, which is one of the most important domain in hydrological cycle, the land-surface models we proposed here integrated soil, vegetation and atmosphere transfer (SVAT) (Gran *et al.*, 2011) to describe the evapotranspiration (ET) process using both energy and water transport in the soil-vegetation-atmosphere system. Together with the new and detailed measurements for the domains of ET would be an alternative to improve the quantifications of evapotranspiration rate and understanding the evapotranspiration process. Such studies are critical to knowing how and why the hydrological dynamics were shifted or changed under the changing environment.

2. Aims of study

This thesis examined the hydrological processes and dynamics under different environment at varying spatial and temporal scales. For this purpose, two types of LULC change were selected: one is a basin undergone **natural disturbance** (bark beetle infestation) in a **mid-mountain forested region**, and another one is a basin undergone **anthropogenic disturbance** (agricultural intensification) in a **semi-arid irrigated region**. Based on these two diverting study areas, pattern-based case studies were conducted to answer the research question:

What are the responses of hydrological dynamics and the related hydro-geochemical conditions to climate change and certain changes in LULC at a basin scale?

Specifically, one case study in the mid-mountain forested environment has undergone a natural disturbance where experienced the abrupt insect-induced forest mortality, our study was conducted to examine the impact of climate change and natural forest disturbance on runoff behaviours and to identify the key hydro-climatic changes. While, another case study a semi-arid irrigated region has undergone an anthropogenic disturbance where historically experienced dramatic changes in hydro-climatic conditions due to both climate change and irrigation practices, our study was conducted aiming to use the multiple climate change scenarios to model possible runoff and its related retention–attenuation of nutrient.

This thesis started from understanding of the changes in hydrological patterns narrowing down to investigate the specific hydrological processes at smaller spatial and temporal scales, including studies aimed to (i) examine significant changes in subsurface chemical composition and in runoff generation processes after bark beetle infestation (at a catchment-scale); (2) address the importance of velocity-celerity difference when studying tracer transport (at a soil column-scale); (3) develop an alternative model to better understand evapotranspiration process under SVAT scheme (at a plot-scale); and (4) quantify the transpiration process and the canopy conductance (at a plot-scale).

3. Material and methods

Study site

Two main research areas (Fig.1) were selected aiming to examine the hydrological conditions at varying spatial and temporal scales. One basin, the Aral Sea Drainage Basin (ASDB) (Fig.1a), undergone anthropogenic disturbance with large-scale irrigation intensification in a semi-arid region of Central Asia. Another basin, the upper Vydra basin (Fig.1b), undergone natural disturbance with bark beetle infestation in a mid-mountain region of Central Europe. Such two terrestrial basins where have diverting environmental problems were used for this thesis together to understand the hydrological processes and dynamics under different environments.

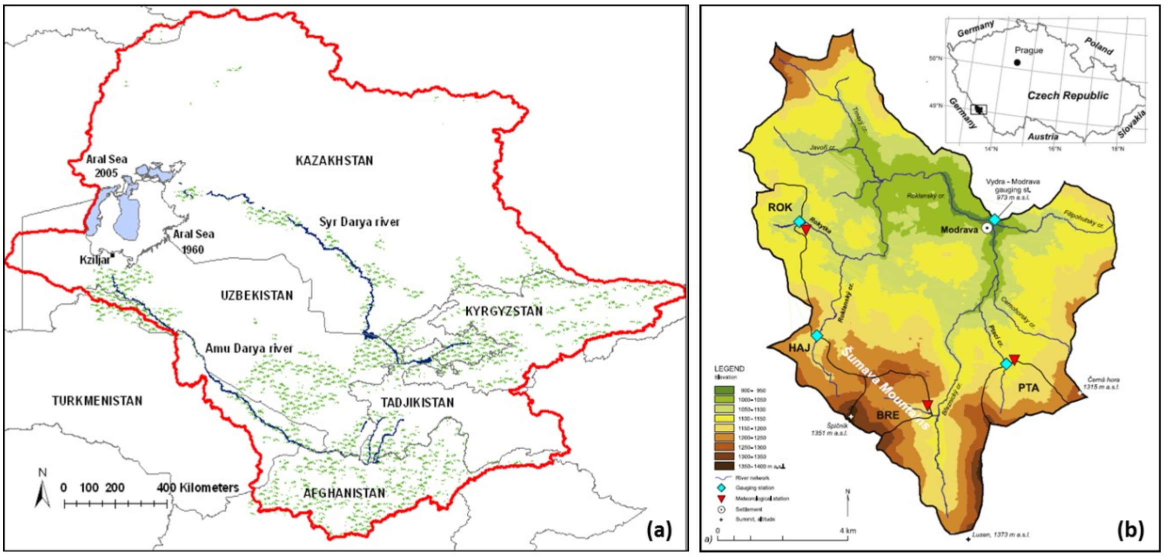


Figure 1. a) *Location of the Aral Sea Drainage Basin, Central Asia,* ***b)*** *location of the upper Vydra basin and 4 nested catchments are given in names of ROK, HAJ, BRE and PTA.*

3.1 Statistical analyses for hydro-climatic trends at a basin scale

For long-term historical study for the upper Vydra basin (Langhammer *et al.*, 2015), daily and monthly hydro-climatic long-term observations (1961–2010) of precipitation, air temperature, and discharge were obtained from the various Czech Hydrometeorological Institution (CHMI) stations. The statistical and analytical methods were applied including double-mass curve analysis, recursive digital filter, Mann-Kendall test, CUSUM analysis, Buishand's and Petitt´s homogeneity tests, and ordinary Kriging to explore the trend of the hydrological regime and investigate the inter-relations between climate warming, forest disturbance, and streamflow at a long-term scale.

3.2 Hydro-climatic modelling at a basin scale

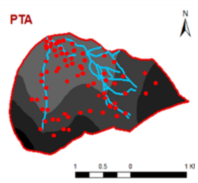
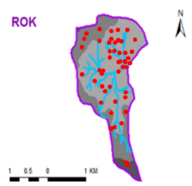
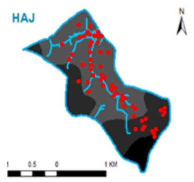
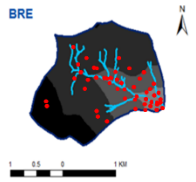
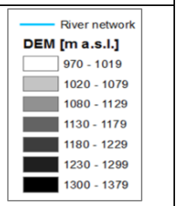
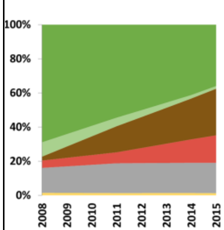
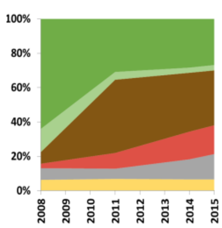
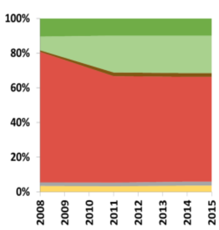
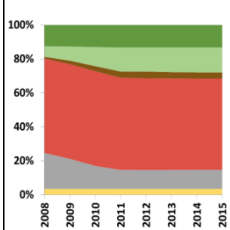
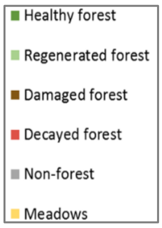
The PCRaster based Polflow model (De Wit 2001) was used to quantify the changes in river discharge from projected future climate change (Shibuo *et al.*, 2007; Törnqvist and Jarsjö, 2012). The semi-distributed hydrological model was based on a water balance approach of $Q=P-ET-\Delta S$. The outputs of the changed T and P (ΔT and ΔP) from 73 GCM projections from the climate model derived from two previous studies (Lioubimtseva and Henebry, 2009; Jarsjö *et al.*, 2012) were used as inputs to the hydrological model. Thereafter, the total prediction envelopes of $\triangle T$ and $\triangle P$ were discretized using even spacing, choosing a resolution that gives a matrix of 11*11 nodes that hence requires a total of 121 runs of the hydrological model leading to 121 sets of △Q (obtained by subtracting Q from current stage result from modelled Q) (Jarsjö *et al.*, 2017). The climatic model based projections of future river flow were further used to estimate possible climate-driven changes in riverine nitrogen concentrations at the outlet.

3.3 Geochemical tracer evaluation model at a catchment scale

In one of our key study sites in the upper Vydra basin (Fig.1b), we further aimed to scale down to its four nested catchments (Table 1), and investigated its possible hydrological and geochemical responses using high frequent hydro-climatic data together with EC to study the responses of hydro-geochemical behaviour. In this process-based study, we traded time for space in understanding the processes of forest decay, degradation, and regeneration in response to streamflow and geochemical conditions at multiple timescales. The hydro-climatic and EC data were aggregated in yearly, daily and hourly values according to the temporal resolutions required by the different analytical methods applied including Mann-Kendall test, Pearson correlation test, Friedman test, etc. Snapshot sampling method was conducted for each site (given as red dots in Table 1) aiming to obtain EC in different locations and at multiple vertical layers including surface water, spring water, soil water, and groundwater.

At the event-scale analysis, the method proposed by Zuecco *et al.* (2016) was used to categorize the EC-Q hysteresis loop, which was used to examine significant changes in subsurface chemical composition and to understand the changes in the runoff generation mechanisms before and after the insect infestation.

Table 1. *Basic physiographic and land cover characteristics of the four experimental catchments. The red dots in the maps indicate the locations taken water samples for snapshot analysis.*

Catchment	**PTA**	**ROK**	**HAJ**	**BRE**	**Legend & unit**
Topography & snapshot locations					
Vegetation dynamics					
Initial year of major infestation	2014 (least disturbed)	2010 (newly disturbed)	< 1996* (highly disturbed)	<1996* (highly disturbed)	

*Note: * the initial year of major bark beetle infestation in HAJ and BRE was between 1984-1995 (Hais et al., 2009; Langhammer et al., 2015).*

3.4 Theoretical analysis at a soil column-scale

Understanding the implications from the above tracer-based study is important due to its complicity. An analytical work (Shao *et al.*, 2018) had been conducted in the thesis here and aimed to provide a clear overview of the relations between celerity (pressure propagation), velocity (water transport), and tracer transport (pore velocity distribution), and to find a new soil hydraulic function for expressing the tracer transport. In this study, the celerity was firstly defined according to the continuum equations based on the conceptualization of a pore bundle model, a mathematical derivation can be done. Under unit hydraulic gradient condition, the celerity function is formulated and further be used to derive a breakthrough curve. The hydraulic characteristic of 5 typical soil textures obtained from the UNSODA database (Leij, 1996) is re-analysed by using the unmodified and modified Mualem-van Genuchten and Brooks-Corey models with standard parameter sets. In the end, the celerity-effective saturation curve was applicable to the bimodal soil hydraulic functions to demonstrate the distributions of pore water velocities.

3.5 Soil-Vegetation-Atmosphere-Transfer (SVAT) model at a plot-scale

An SVAT model was developed and tested in two types of vegetated plots covering with maize (Shao *et al.*, 2018) and forest (Shao *et al.*, 2017), and both plots had comprehensive monitoring dataset of water and energy fluxes that can validate its utility and accuracy. We also implemented in one of our experimental catchments in ROK (see more detail of this study plot in Fig.3a).

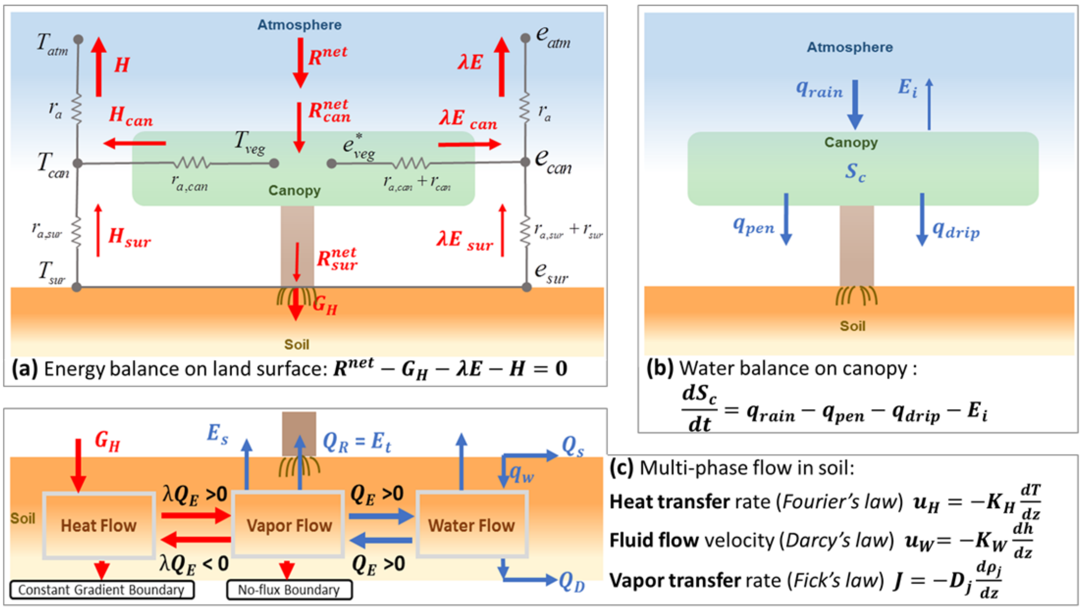


Figure 2. *SVAT Model conceptualization and governing equations/theories of each module. E_t, E_S and E_i is transpiration, soil evaporation, and canopy interception evaporation. All red arrows represent the energy flux and the blue arrows indicate water flux. Air temperature, precipitation, wind, and humidity are the input for the model. The detailed components and used coupling approaches.*

The model was conceptualized the energy and water transport in three modules (Fig. 2). The land-surface module in Fig.2a contains a two-layer energy network to facility the partitioning of the evapotranspiration into transpiration E_t, soil evaporation E_s, and interception evaporation E_i, which driven by the energy fluxes component of latent heat λE, sensible heat H and ground heat fluxes G and connected with resistance coefficients (given as black font in Fig. 2a). The canopy hydrology in Fig. 2b describes that rainfall q_{rain} initially reaches the vegetation canopy, some of which can penetrate through the canopy directly reaching the soil surface q_{pen}, while some of which will be intercepted by the leaves and branches of vegetation canopy S_c, and along with the canopy interception storage increasing, throughfall and stem flow (summed as water dripping) will be formed q_{drip}. The soil multi-phase flow in Fig. 2c describes the water, vapour, air, and heat transport in a root zone to more accurately describe the energy balance in the subsurface system. The liquid water flow is described by the Darcy-Richards equation, the upper boundary conditions include flux boundary condition for non-ponding infiltration and the pressure head boundary when ponding and overland flow occurs. The vapour flow (gas phase) is a convection-diffusion equation with upper boundary of soil evaporation rate, and the air flow is simplifying considered to enhance evaporation during the drought condition. The heat flow equation includes thermal convection (originated from mass transport of water, air and vapor flow), and thermal conduction.

3.6 Sap flow experiment and stomatal conductance model at a plot scale

A sap flow experiment, along with soil profile monitoring, was carried out in one experimental plot at one of the nested small catchments in the upper Vydra basin, ROK (Fig. 3a). The 3-month high-frequent measurements enabling us to investigate quantify the transpiration process in Century European mid-mountain beech forest in a more detailed level. Six beech trees with different ages and truck diameters were installed with EMS 81 sap flow sensor (EMS Brno, CZ) (Fig.3c) within a square area (30x30 m) of 900 m² in this study (Fig. 3b). The square area consisted of 32 beech trees with the mean age of 55 years and the mean trunk diameter of 0.9 m (at height of 1 m).

The obtained transpiration rate E (mm s^{-1}) was further used to infer the stomatal conductance g_c(m s^{-1}) by inversely estimated by rearranging the PM type equation (Su *et al.*, 2019):

$$g_c = \frac{g_a \gamma \lambda E}{\Delta R_{can} + \rho_a C_p (e_s - e_a) g_a - \lambda E (\Delta + \gamma)} \quad (1)$$

Hereafter, considering the impact of multiple environmental factors on stomatal conductance, this study adopted the Jarvis-Stewart model (JS) (Jarvis, 1976; Stewart, 1988) consists of multiplicative nonlinear functions of environmental variables (Jarvis, 1976; Zhang *et al.*, 2011; Naithani *et al.*, 2012; Wang *et al.*, 2014):

$$g_c = I_{LAI} g_{c,max} \prod_i F_i(x) \quad (2)$$

The functions F_i are a set of scaling terms that reduced a maximum value of canopy conductance ($g_{c,max}$) in response to changes in net radiation (R_s), vapour pressure deficit (D), temperature (T), and soil water content (θ). The values of functions F_i range between 0 and 1, therefore any changes in the values of R_s, D, T, and θ will proportionally modify the parameters $g_{c,max}$ to give an estimations of g_c controlling transpiration rate.

Moreover, the impact of parametrization of stomatal conductance on transpiration rate was quantified with two methods: one used inversely estimated stomatal conductance, and the other used typical stomatal conductance of broad leaf forest adopted from a lookup table in an existing literature. Finally, the pattern of transpiration rate during the transition period from vegetative period to defoliated period was analysed.

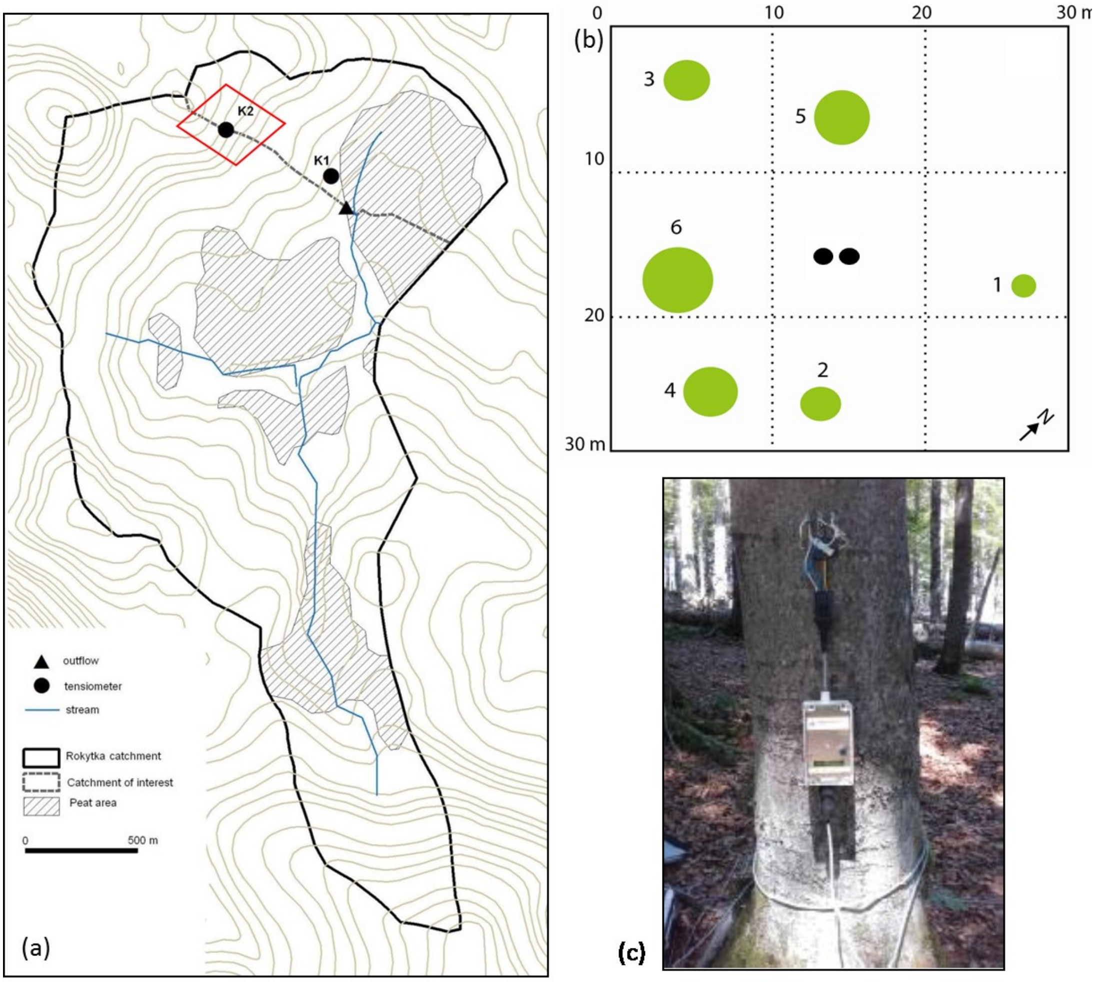


Figure 3. ***(a)*** *Study area –ROK and the location of the plot.* ***(b)*** *Scheme of tree distribution for sap flow measurement at the 30x30 m experimental plot. The size of the green dot represents the size of the tree trunk.* ***c)*** *Photo of one installed EMS 81 sap flow device at 1 m above the ground in Tree No. 1.*

4. Results and discussion

4.1 Impacts of climate change and LCLU change on hydrological conditions at a basin scale

The study in the upper Vydra basin, Central Europe, the long term hydro-climatic changes over the period of 1961-2010 were analysed, and the results showed a clear increasing trend of annual air temperature, which was occurring in the rest of the world including another study area in Central Asia. Under the climate warmer, the annual precipitation did now show a consistent tendency in two places due to heterogeneity of climate-land-vegetation-soil feedback. However, the apparent change of the hydrological regimes was observed in both places, which all causing changes in their geochemical conditions.

In the upper Vydra basin, the forest disturbance was an add-in driving factor since the 1990s, and the observed changes mainly occurred in runoff seasonality and intra-annual variability but not the annual runoff balance (Langhammer *et al.*, 2015). The seasonal runoff shifted from summers by an 18% decrease to springs by a 10% decrease (Fig.4a), which could largely attribute to the climate-driven changes in the snow-melting process. The occurrence of peak flows (POT) doubled but shifted from late spring to early spring (Fig. 4b), while the occurrence of low flow (LOF) shifted from autumn to mid-winter with a two-thirds decrease in days till 1990 followed an increase (Fig. 4c). Changes in POT and LOF may be caused by changes in forest cover due to bark beetle infestation. The observed runoff regime change indicates the sensitivity of the mid-latitude montane basin to climate change as well as to land cover change, and the inconsistency of the changes worldwide highlight the importance of more studies from varying environment.

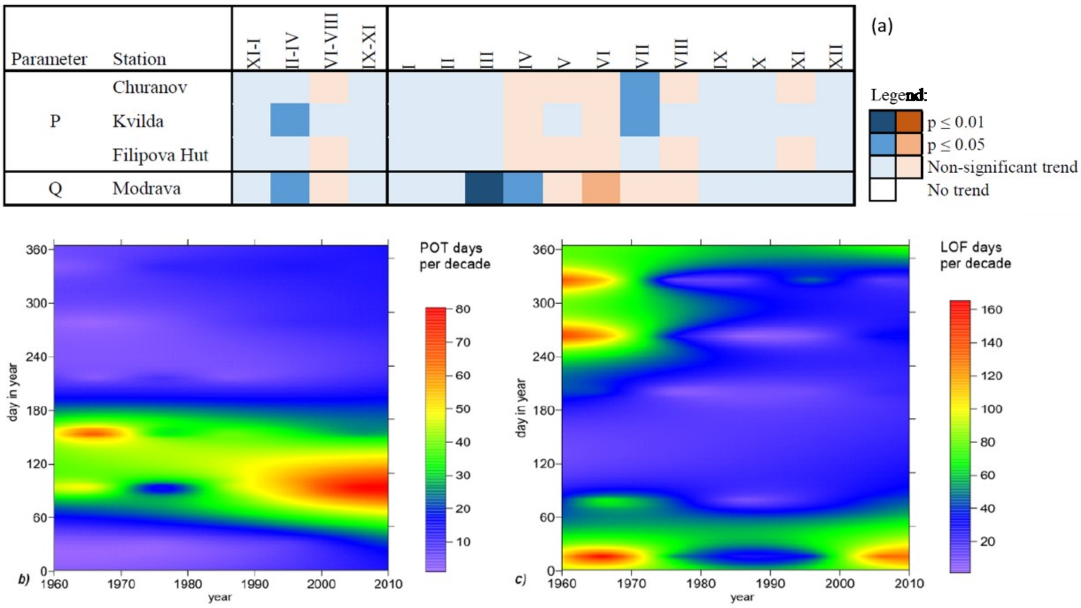


Figure 4. (a) *Mann-Kendall test of seasonal and monthly trend of P and Q during 1961-2010. Blue indicates an increasing trend while red indicates a decreasing trend, and darker colour indicates a more significant trend.* ***(b)*** *Changes in frequency and seasonality of days with POT; and* ***(c)*** *Changes in frequency and seasonality of days with LOF.*

Unlike the small basin, in the ASDB, when the spatial scale increased up to the large basin, the temporal scale was enhanced to annual mean conditions. The annual runoff decreased by around 70 $km^3 \cdot year^1$ during the 1960-2000, and the N fertilizer application in the ADRB and the water recirculation rate were increased. For the basin covering 1.3% of the earth's land with high population, the future climate-driven projections of changes in runoff regime and nitrogen retention-attenuation are crucial for the regional management and planning. The converge of 73 multi-model projections that $\triangle T = 5°C$ and $\triangle P = 13\ mm \cdot year^1$ in the region will likely cause $\triangle Q = -7\ km^3 \cdot year^1$ (negative value indicates decrease comparing to the current condition) till 2100 in its principal Amu Darya River in 2100 (Fig.5a). As projected (Jarsjö *et al.*, 2017), once $\triangle Q = -4\ km^3 \cdot year^1$, the degree of river water and irrigation water re-use (the recirculation ratio, r) will change from the current value of 5.7 to over 100 in 2100 under both scenarios (Fig. 5ab). Using a basin-scale analytical recirculation model adopted for nitrogen loading conditions of ADRB, the climate-driven enhancement of r-value may considerably decrease the riverine DIN-concentrations at the outlet (Fig. 5c). More generally, if current agricultural practices are maintained in ADRB, the recirculation of already saline return flows may increase in the future as the result of climate-related water shortage. The present results furthermore imply that such high sensitivity of riverine nitrogen concentrations to climate change can be common in highly managed basins across the world.

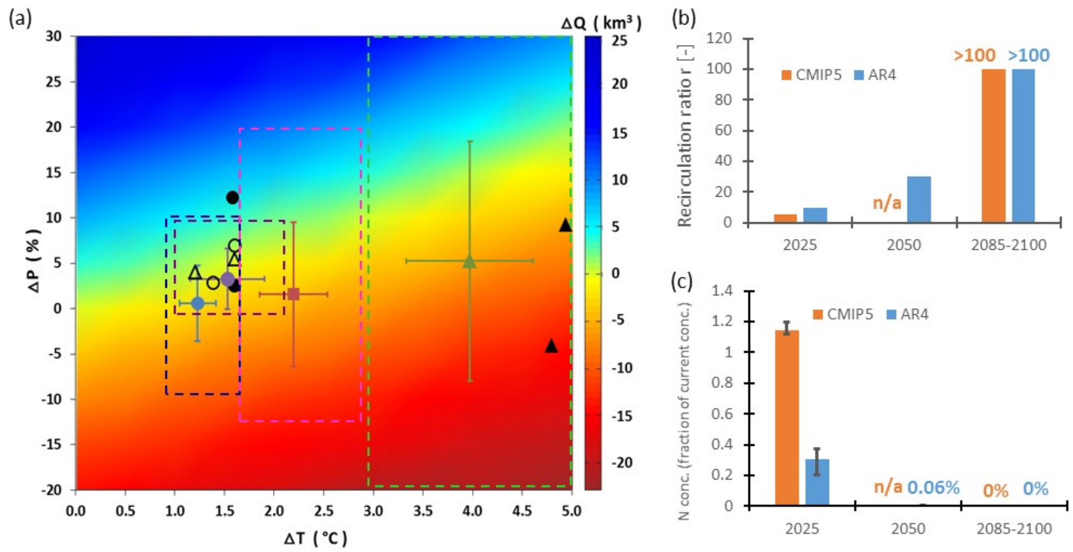


Figure 5. *(a) The modeled flow change △Q in the Amu Darya river near its outlet, in response to windows of △T and △P combinations that covers all △T and △P combinations of the considered 73 GCM projections (Jarsjö et al. 2011, Lioubimtseva and Henebry 2009). The ensemble mean values and standard deviation of the multi-model output are indicated with colored symbols and error bars;* ***(b)*** *r-value of ADRB and* ***(c)*** *N concentrations in its downstream river water in the years 2025, 2050 and around 2085-2100.*

4.2 Geochemical response after bark beetle infestation and tracer transport theory

Catchment-scaled study in the upper Vydra was focusing on understanding the impact of the bark beetle infestation induced land cover change in small catchments within the upper Vydra basin. Four catchments featuring different stages of forest disturbance representing least disturbed catchment, newly disturbed catchment, and two highly disturbed catchments depending on its extent and initial year of the infestation. The EC characteristics in those 4 catchments in Fig. 6 showed the differences in EC from different water sources and from their stream water, such results from snapshots experiment assisted on understanding the runoff generation processes, and analysing the followed up results for different timescales given in Table 2).

From multiple timescales analysis, we found that the changes of runoff-EC relations are inter-related. For instance, the infestation-induced changes in event-scale dynamics may be largely responsible for the observed shifts in annual average conditions. A comparison of the EC response patterns of catchments with newly disturbed and those in regions severely infested prior to the monitoring period together proved that hydrogeochemical conditions in the disturbed catchments have relatively long-lasting effects. As the climate-driven bark beetle outbreaks will likely spread in the mid-latitudes, our study provided a better understanding of the mechanisms behind the hydrogeochemical changes in catchments following insect infestation.

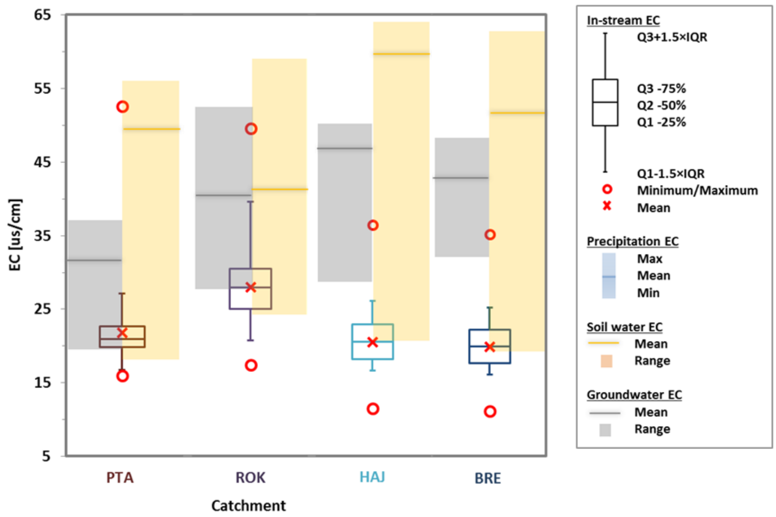


Figure 6. *The EC characteristics in streams, soil, and ground water, and precipitation.*

Table 2. *Summary of the findings from Su et al. (2017), listing the effects of insect-induced forest disturbance on in-stream EC at multiple timescales. Fig. 6 summarized the EC characteristics in each studied catchment, which assist in interpreting the findings.*

Timescales	Key findings	Implications
Annual	• Increased annual average in-stream EC values in the bark beetle-infested catchments, with particularly elevated EC values during base flow conditions. • Associated with the initiation of regeneration in the highly disturbed catchments, EC decreased. • No trend in annual average R and RC in any of the considered catchments.	• Increased EC is caused by the cumulative loading of soil water and groundwater that discharge excess amounts of substances such as nitrogen and carbon, which are released via the decomposition of the needles, branches, and trunks of dead trees, into streams. • Decreased EC is likely caused by vegetative uptake of the excess nitrogen. • The expected runoff increase related to transpiration loss and interception reduction (due to tree mortality) was small or masked by other factors.
Seasonal	• Consistently yielded similar increasing EC trends during all four seasons, in particular the trend is clear in the least disturbed catchment and in the newly disturbed catchment.	
Daily	• Daily EC variability was larger in the least disturbed catchment and in the newly disturbed catchment than two highly disturbed catchments, which was related to elevated instream EC under base flow conditions.	• The mobilization and downward percolation of nutrients and carbon from litter and decomposing needles may be considerable after infestation-induced tree mortality even during moderate rain and infiltration events. • The lack of nutrient uptake by trees could further enhance the cumulative loading of groundwater that discharges into the streams. When the system is flooded under event conditions, substance-enriched soil water and groundwater may be mixed with and diluted by low-salinity event water in a similar manner.
Event	• The positive EC-Q relationships and counter clockwise hysteresis loops were observed in the least disturbed catchment and during the early period of the newly disturbed catchment. • In the highly disturbed catchment, the decreasing EC in response to increasing Q at the beginning of the events as well as the net decrease in in-stream EC during the course of the events	• Healthy forest system required event flows to mobilize substances in the soil and groundwater systems, and a large fractions of total annual in-stream substance loads are released during limited peak flow periods. • When the system is flooded under event conditions, substance-enriched soil water and groundwater may be mixed with and diluted by low-salinity event water, leading to a negative EC-Q relationship.

The difference of velocity and celerity for expressing the speed of tracer/mass flow and flood wave was studied (see Table 3) and highlighted the importance of understanding the tracer transport, which helped us to understand the implications in tracer-based studies. However, the proposed celerity function is still at the theory stage based on a pore bundle model, which will need more experiments to testify the feasibility to use in the hillslope scale and catchment scales. This theoretical analysis only offered a breakthrough perspective when we using any type of tracer in the water system, to distinguish the flood wave away from the tracer transport.

Table 3. *Constitutive relationships under the unit hydraulic gradient condition formulated by the Brooks-Corey model and the modified Mualem -van Genuchten model*

Property	Definition	Brooks-Corey	Modified Mualem-van Genuchten
Water retention	$\Theta = f(h)$	$\Theta = \begin{cases} \lvert\alpha_{\mathrm{BC}} h\rvert^{-n_{\mathrm{BC}}}, & \alpha_{\mathrm{BC}} h < -1 \\ 1, & \alpha_{\mathrm{BC}} h > -1 \end{cases}$	$\varepsilon\Theta = \begin{cases} \left[1 + \lvert\alpha_{\mathrm{VG}} h\rvert^{n_{\mathrm{VG}}}\right]^{-m_{\mathrm{VG}}}, & h < h_s \\ 1, & h \geq h_s \end{cases}$
Specific discharge	$q = K$	$K_s \Theta^{\frac{2}{n_{\mathrm{BC}}}+3}$	$K_s \Theta^{l_{\mathrm{VG}}} \left[\frac{1-\left(1-(\varepsilon\Theta)^{1/m_{\mathrm{VG}}}\right)^{m_{\mathrm{VG}}}}{1-(1-\varepsilon^{1/m_{\mathrm{VG}}})^{m_{\mathrm{VG}}}} \right]^2$
Average pore velocity	$\bar{v} = \frac{q}{\theta - \theta_r}$	$\frac{K_s}{\theta_s - \theta_r} \Theta^{\frac{2}{n_{\mathrm{BC}}}+2}$	$\frac{K_s}{\theta_s - \theta_r} \Theta^{l_{\mathrm{VG}}-1} \left[\frac{1-\left(1-(\varepsilon\Theta)^{1/m_{\mathrm{VG}}}\right)^{m_{\mathrm{VG}}}}{1-\left(1-\varepsilon^{1/m_{\mathrm{VG}}}\right)^{m_{\mathrm{VG}}}} \right]^2$
Celerity	$c = v = \frac{dK}{d\theta}$	$\frac{a_K K_s}{\theta_s - \theta_r} \Theta^{\frac{2}{n_{\mathrm{BC}}}+2}$	$\frac{a_K K_s}{\theta_s - \theta_r} \Theta^{l_{\mathrm{VG}}-1} \left[\frac{1-\left(1-(\varepsilon\Theta)^{1/m_{\mathrm{VG}}}\right)^{m_{\mathrm{VG}}}}{1-\left(1-\varepsilon^{1/m_{\mathrm{VG}}}\right)^{m_{\mathrm{VG}}}} \right]^2$
Kinematic ratio	$\alpha_K = c/\bar{v}$	$\frac{2}{n_{\mathrm{BC}}} + 3$	$l_{\mathrm{VG}} + \frac{2\left[1-(\varepsilon\Theta)^{1/m_{\mathrm{VG}}}\right]^{m_{\mathrm{VG}}-1} (\varepsilon\Theta)^{1/m_{\mathrm{VG}}}}{1-\left[1-(\varepsilon\Theta)^{1/m_{\mathrm{VG}}}\right]^{m_{\mathrm{VG}}}}$

Notation of Table: *α (L^{-1}) n (-) and m (-) are the fitting parameters for the Brooks-Corey model (detonated with subscription of "BC") and Mualem-van Genuchten model (detonated with subscription of "VG"); Θ is effective saturation (-) that is defined as: $\Theta = (\theta - \theta_r)/(\theta_s - \theta_r)$; ε is the correction factor to modify the van-Genuchten model $\varepsilon = (\theta_s - \theta_r)/(\theta_m - \theta_r)$, with $\theta_m = \theta_r + (\theta_s - \theta_r)\left[1 + \lvert\alpha_{\mathrm{VG}} h_s\rvert^{n_{\mathrm{VG}}}\right]^{m_{\mathrm{VG}}}$, h_s is the minimum capillary height, which becomes zero when $\theta_m = \theta_s$, l_{VG} is pore connectivity parameter, and is usually assumed to be 0.5.*

4.3 Evaporation processes

Estimating evaporation in forest area, the commonly used the Penman-Monteith equation coupled with the Richards' equation underestimated the total evaporation rate, while the SVAT model integrating a non-isothermal multi-phase flow model with a two-layer energy model largely improved the model accuracy (Fig. 7). Our propose SVAT model was further testified its performance in cropland (Shao *et al.*, 2018) with varying LAI, which helped to examine the model accuracy throughout the entire vegetation period from non-vegetated to LAI=3.2. The importance of considering advective vapour transport in simulating soil moisture content and temperature at the soil surface was studied in a forested plot (Shao *et al.*, 2017), which further can affect the simulated evaporation fluxes. An extended test was conducted for one experimental plot in ROK of the upper Vydra basin.

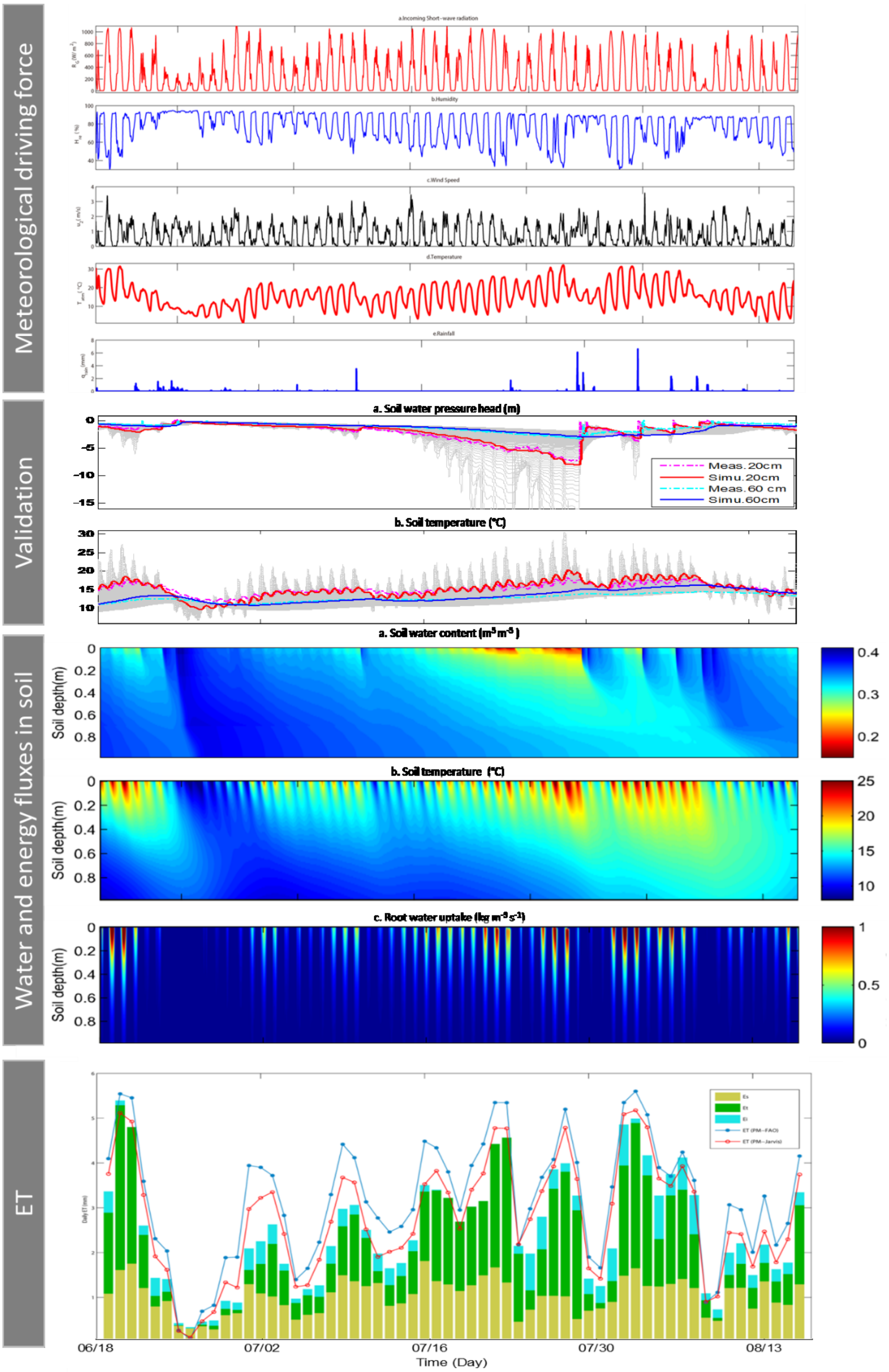


***Figure** 7. Simulations of a 2-month vegetation period in ROK catchment (in upper Vydra basin) in the year of 2013 by using our proposed SVAT model*. Calculated ET was given *from FAO Penman–Monteith model (i.e. reference evaporation; red line), evaporation estimated by PM-JS with calibrated parameters (blue line), and SVAT model (cumulative bar from three different green).*

The forcing climate data (given in Fig. 7a) was used in the proposed model for partitioning the evaporation rate in the experimental catchment ROK. The well-fittings of the soil temperature, and pore water pressure head suggested that the soil physics behaviour was well described by the proposed model. Fig. 7 showed the ability of the model, it can model different components of ET rate, enabling understand the evaporation process in more detail. In particular, such model would be useful for projecting the future change in such area with forest disturbance. The functionality of the vegetation under the dry or water deficit condition alters the ET rate, which would be neglected from the simple model. From another perspective, the capacity of vegetation transpiration is lower when there is less water in the soil, consequently, when the temperature increases as projected by climate change models, the total ET amount from the vegetation should decrease. Such an effect will not be considered in any of the simple models for calculating ET. During the simulation period, the soil moisture dynamic controls the resistance coefficient of soil surface and foliage stomata resistance (i.e, canopy conductance), and furthermore the energy fluxes of latent heat components. Therefore, we conducted sap flow measurements to understand local transpiration process (Su *et al.*, 2019), and used sap flow to reversely calculate the canopy conductance and examining the goodness of such a method. We can effectively use calculated conductance to either calculate the evaporation (Fig. 7), and the results showed large consistency with the measurements. Such an approach offers a new way to estimate the ET in the area with less monitoring.

Apart from the lumped information from the sap flow measurements, the knowledge on the diurnal pattern of the six individual trees with different ages were obtained in Fig. 8. We can see the tree age led to the difference in absolute value of transpiration but the diurnal pattern of this tree species responding to certain climatic conditions are identical. With such information we can classify the forest in the catchment, and calculated the ET in more accurate way.

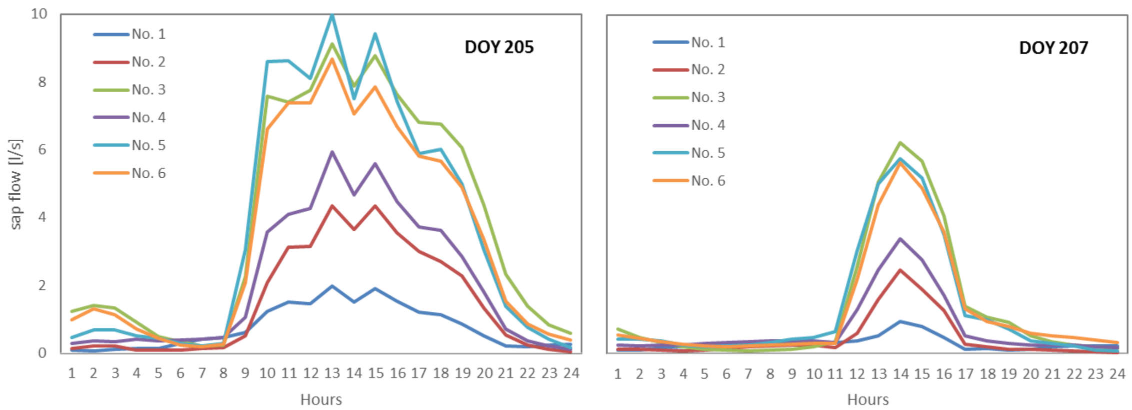


Figure 8. *The diurnal pattern of the measured sap flow in 6 trees (the sizes of the six trees in corresponding numbers are given in Fig. 3b) at two selected days – DOY 205 and DOY 207.*

5. Conclusion

The thesis was focused on understanding the hydrological processes and behaviours, which was based on analysing the historical data, developing proper models, and conducting an in-site experiment. Two key study areas were located in two basins of diverting environment in Central Asia and Central Europe, where have different environmental problems but all sharing one common driving factor - climate change. Under the changing climate over nearly half-century, two different environment offered deep insights on how the earth was altered on the hydrological system.

- In the upper Vydra basin (mid-mountain in Central Europe) experiencing forest disturbance and climate change, statistically found even the annual water balance over had no apparent change, regional runoff regime at smaller temporal scale was altered.
- Warmer climate and bark beetle-induced tree mortality in the upper Vydra basin affected **seasonal runoff** (shifted from summers to springs), **occurrence of peak flow events** (doubled since the 1980s with a seasonal shift from late spring towards the early spring), and **occurrence of low flow events** (dropped two-thirds with a seasonal shift from autumn to mid-winter).
- In the Aral Sea Drainage Basin (a semi-arid region in Central Asia, covering 1.3% of the earth's land surface) experiencing intensive agriculture and warmer climate, the **decrease in annual runoff** of the principal river Amu Darya and **an increase of internal recirculation ratio** were found in historical data.
- Climate-driven projections for the ASDB found most likely river flow will **continuously decrease** at the basin outlet, which will **increase internal nutrient recirculation ratios, average transport distances, and attenuation**.

This thesis started from an understanding of the changes in hydrological patterns narrowing down to investigate the specific hydrological processes at smaller spatial and temporal scales, covering studies on the geochemical transformation, tracer transport, and evapotranspiration process. Knowledge and lessons we learnt from theoretical analysis, modelling, and in-site experiment were summarized below.

- Geochemistry at the catchment scale changed over studied 7 years at multi-timescale after bark beetle infestation, and the changes in the disturbed catchments were **rapid after extensive infestation and last long over decades**.
- Along with tree mortality, **increased annual mean in-stream electrical conductivity (EC)** is likely caused by the cumulative loading of soil water and groundwater with substances of nitrogen and carbon released by dead trees. The observed **EC decreases** associated with the initiation of regeneration in the affected catchments was likely caused by vegetative uptake of the excess nitrogen.
- After infestation the **EC-discharge hysteresis loops at the event-scale shifted from positive to negative** relationships, implying changes in the subsurface chemical composition and in the interactions with runoff.
- The proposed **celerity function** has been theoretically proved the usefulness when assist in studying subsurface flow and tracer transport, in particular **the kinematic ratio** (a ratio between celerity and average velocity) could be used to predict the first arrival time of a tracer.

- A **newly proposed model** coupling an SVAT model with a non-isothermal multi-phase flow model was applied in two different environment (forest and maize), and the performance was better due to more detailed description of energy transfer and the formation of advective soil vapour transport.
- **Reversely-calculated canopy conductance** based on **sap flow measurement** had substantially improved the estimation of transpiration during the vegetative period, which can help to better understand the evapotranspiration process in newly form beech stands after bark beetle outbreaks in central Europe.

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EDUCATION BACKGROUND:

10/2012-now **Charles University, Czechia**

PhD researcher of hydrology, climate change and land cover

09/2010-04/2012 **Stockholm University, Sweden**

Master of Hydrology, Hydrogeology and Water Resources

09/2009-07/2010 **Utrecht University, Netherlands**

Master of Environmental Science – Sustainable Development

09/2005-07/2009 **Beijing Forestry University, China**

Bachelor of Agriculture – Soil and Water Conservation

PROJECTS & RESEARCHES:

10/2012-Now Participated in the projects: GAČR P209/12/0997, EU COST Action ES1306 LD 15130S, GAČR 19-05011S, and was studying the impacts of climate change and forest disturbance on ecohydrological dynamics in the changing environment and was using models including hydrological models and land surface models to study the processes in the physical geography.

11/2010-4/2012 Completed master thesis - "The Impacts of Climate Changeon River Flow and Riparian Vegetation in the Amu Darya River Delta, Central Asia" from Stockholm University using hydro-climatic models.

02/2010-08/2010 Worked in UN-Habitat in peri-urban of Kathmandu Valley for evaluating water supply and sanitation interventions in Nepal, and completed master thesis "sustainability assessment of water supply and sanitation interventions" in Utrecht University

CONFERENCES & ACTIVITIES

10/2018 **Research visiting** in University of Zürich, Switzerland

Presented in the hydrology team and established potential collaboration

04/2015 **EGU conference 2015** in Vienna

Participated in 3 sessions by contributing: "Analysing the influence of preferential flow on pressure transmission and landslide triggering", "Can flow velocity distribution at a pore-scale be quantified by a celerity-saturation curve?", and

	"Quantifying the feedback of evaporation and transpiration rates to soil moisture dynamics and meteorological condition changes by a numerical model"
04/2014	**EGU conference 2014** in Vienna
	Participated in 3 sessions by contributing: "Response of basic hydro-chemical indicators to rainfall-runoff events in forest disturbed catchments in upper Vydra, Central Sumava Mountains.", "Hydrological response to forest disturbance under a changing climate in experimental headwater basins, Central Sumava Mountains", and " Climate change and forest disturbance effect on runoff response in montane basin. Case study-Vydra basin, Sumava Mountains"
11/2013	**Research visiting** in Delft University of Technology, Netherlands
	Established long-term collaboration
04/2013	**EGU conference 2013** in Vienna
	Participated in 2 sessions by contributing: "Catchment-scale contaminant transport under changing hydro-climatic conditions in the Aral Sea Drainage Basin, Central Asia", and "Impact of forest disturbance on the runoff response in headwater catchments. Case study: Sumava Mountains, Czech Republic"
04/2013	**Summer course** in CRP - Gabriel Lippmann, Belvaux, Luxemburg
	"Model building, inference and hypothesis testing in conceptual hydrological modelling"

ADDITONAL INFORMATION

- **Computer Ability:** MS, MATLAB, Auto CAD, C++, ArcGIS, SPSS, GAMS, PCRaster, Python
- **Language:** Native speaker of Chinese (mandarin), fluent in English, and basic level in Czech (A1)

PUBLICATIONS (2014-2019)

*corresponding author

Su, Y. *, Shao, W., Vlcek, L. and Langhammer, J., 2019. Ecohydrological behaviour of mountain beech forest: quantification of stomatal conductance using sap flow measurements. Geosciences, 9(5), 243. DOI: 10.3390/geosciences9050243. (**IF 1.820**)

Shao, W., Yang, Z., Ni, J., **Su, Y.**, Nie, W., Ma, X., 2018. Comparison of single- and dual-permeability models in simulating the unsaturated hydro-mechanical behavior in a rainfall-triggered landslide. *Landslides*. DOI: 10.1007/s10346-018-1059-0. (**IF 3.811**)

Shao, W., Coenders-Gerrits, M., Judge, J., Zeng, Y., **Su, Y.***, 2018. Simulation of non-isothermal soil moisture transport and evaporation fluxes in a maize cropland. *Journal of Hydrology*, 561, 833-847. DOI: 10.1016/j.jhydrol.2018.04.033. (**IF 4.314**)

Shao, W., **Su, Y.***, Yang Z., Ma, X., Langhammer, J., 2018. Quantify the pore water velocity distribution by a celerity function. *Geofluids*, 2018, 19. DOI:10.1155/2018/1054730. (**IF 2.540**)

Shao, W., **Su, Y**., Langhammer, J., 2018. Simulations of coupled non-isothermal soil moisture transport and evaporation fluxes in a forest area. *Journal of hydrology and hydromechanics*, 66, 1-6. DOI: 10.1515/johh-2017-0038. (**IF 1.564**)

Su, Y., Langhammer, J., Jarsjo, J., 2017. Geochemical responses of forested catchments to bark beetle infestation: Evidence from high frequency in-stream electrical conductivity monitoring. *Journal of Hydrology*, 550, 635-649. DOI: 10.1016/j.jhydrol.2017.05.035. (**IF 4.314**)

Jarsjo, J., Törnqvist, R., **Su, Y.**, 2017. Climate-driven change of nitrogen retention–attenuation near irrigated fields: multi-model projections for Central Asia. *Environmental Earth Sciences*, 76, 117. DOI:10.1007/s12665-017-6418-y. (**IF 1.435**)

Shao W., Ni, J., Leung, A.K, **Su, Y.**, Ng., C.W.W., 2017. Analysis of plant root-induced preferential flow and pore water pressure variation by a dual-permeability model. *Canadian Geotechnical Journal*. DOI: 10.1139/cgj-2016-0629. (**IF 2.911**)

Shao, W., Bogaard, T., Bakker, M., **Su, Y.**, Berti, M., 2016. Coupling a 1D dual-permeability model with an infinite slope stability approach to quantify the influence of preferential flow on slope stability. *Procedia Earth and Planetary Science*, 16, 128-136. DOI: 10.1016/j.proeps.2016.10.014

Langhammer, J., **Su, Y.**, Kaiglová, J., 2015. Runoff Response to Climate Warming and Forest Disturbance in a Mid-Mountain Basin. *Water*, 7, 3320-3342. DOI:10.3390/w7073320. (**IF 2.069**)

Langhammer, J., Hartvich, F., Kliment, Z., Jeníček, M., Bernsteinová, J., Vlček, L., **Su, Y.**, Štych, P. Mičijovský, J. 2015. The impact of disturbance on the dynamics of fluvial processes in mountain landscapes. *Silva Gabreta*, 21 (1), 105–116.

Su, Y. and Langhammer, J., 2014. Feasibility of using a salt tracer dilution method to estimate streamflow in small mountainous catchments in the Sumava Mountains. *Proceedings of International Scientific Conference CER 2014*, London, Issue 2, p106-109.