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温帯ヒノキ林における蒸発散量の年々変動とその決定要因の解明
Interannual variations and its control factors of evapotranspiration in a temperate Japanese cypress forest

鶴田 健二 [1*] ; 小杉 緑子 [1] ; 高梨 聡 [2] ; 谷 誠 [1]
TSURUTA, Kenji[1*] ; KOSUGI, Yoshiko[1] ; TAKANASHI, Satoru[2] ; TANI, Makoto[1]

[1] 京都大学大学院農学研究科, [2] 独立行政法人森林総合研究所
[1]Graduate School of Agriculture, Kyoto University, [2]Forestry and Forest Products Research Institute

1. 背景

森林の蒸発散は流出量ひいては水資源量に影響を及ぼす主要な要素である．近年，各地で報告されている年平均気温の上昇や降水特性の変化が蒸発散量に及ぼす影響を評価するためには，長期で蒸発散量の計測を行い，その変動要因を明らかにしておく必要がある．そこで本研究では，日本の主要な森林タイプであるヒノキ林において乱流変動法による蒸発散量の計測を 7 年間継続して行い，その年々変動の変動幅を定量化するとともに，多層モデルを用いることで蒸発散量の変動要因を特定した．

2. 方法

試験地は滋賀県南部に位置する桐生水文試験地である．本試験地は林齢約 50 年生，樹高約 19 m，葉面積指数約 4.5?5.5 のヒノキ林で覆われている．試験地内に設けられた微気象観測タワーを使用して林冠上の気象観測を行うとともに，乱流変動法により林冠上の顕熱・潜熱フラックスを計測した．エネルギーインバランスの補正を行うために，ボーエン比に応じて顕熱・潜熱フラックスの補正を行った．潜熱フラックスの欠測値は，有効エネルギーと潜熱フラックスの関係を用いて補完した．雨量の観測は試験地内の露場において行った．

蒸発散量の年々変動の決定要因を特定するために，多層モデルを用いた解析を行った．多層モデルには放射伝達モデルや光合成・蒸散モデルなどのガス交換に関わる各種サブモデルが含まれ，林冠上の気象要素を入力環境変数として，植生内の気象要素の鉛直プロファイルおよび植生‐大気間の顕熱・潜熱・CO2 フラックスを求めることができる．モデル中のパラメーターは本試験地おける個葉のガス交換測定などを基に決定した．なお，解析期間は 2001 年～2007 年である．

3. 結果と考察

7 年間で蒸発散量は 2004 年が 780 mm year-1 で最も大きく，2001 年が 715 mm year-1 で最も小さかった．蒸発散量の 7 年平均は 743 mm year-1 となり，最大で 75 mm 程度の年々変動が確認された．

多層モデルを用いて蒸発散量の再現計算を行ったところ，蒸発散量の日変化および 7 年間の年々変動を良好に再現することができ，モデル構造とパラメタリゼーションは妥当であると考えられた．

蒸発散量を蒸散・遮断蒸発・林床面蒸発の要素別に分離評価したところ，気象条件に対応した各要素の年々変動が認められた．降水量が少なかった 2001 年や 2002 年は遮断蒸発が少なく，蒸散が多かった．一方で，降水量が多かった 2003 年や 2006 年は遮断蒸発が多く，蒸散が少なかった．2004 年は遮断蒸発・蒸散ともに多かった．林床面蒸発は蒸散・遮断蒸発に比べて量的に小さく，年々の変動幅も小さかった．

7 年間のうち，対照的な 2 年（年蒸発散量計算値が最大となった 2004 年および最小となった 2003 年）の蒸発散量の季節変化を調べたところ，蒸発散量は 6 月～8 月の夏季に平均値からの差が大きくなっていた．蒸散は大気飽差や日射量が大きいほど増加する傾向にあり，夏季に大気飽差や日射量が小さかった 2003 年は蒸散量が小さく，大気飽差や日射量が大きかった 2004 年は蒸散量が大きかった．林床面蒸発にも同様の傾向が認められた．また，遮断蒸発は降水量に対応した季節変化を示した．

以上のことから，蒸発散量の年々変動は気象要素の変動で概ね説明可能であり，蒸散・遮断蒸発・林床面蒸発の気象要素に対するそれぞれ異なる応答の違いにより生じているものと考えられた．

キーワード: 蒸発散, 年々変動, 乱流変動法, 多層モデル, ヒノキ林
Keywords: Evapotranspiration, Interannual variation, Eddy covariance, Multi layer model, Japanese cypress forest

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九州地方の人工林小流域における蒸発散と水利用効率について
Evapotranspiration and water use efficiency on a coniferous planted forest watershed in south western Japan

清水 貴範 [1*] ; 玉井 幸治 [1] ; 熊谷 朝臣 [2] ; 石塚 成宏 [3] ; 大谷 義一 [1] ; 清水 晃 [3]
SHIMIZU, Takanori[1*] ; TAMAI, Koji[1] ; KUMAGAI, Tomo'omi[2] ; ISHIZUKA, Shigehiro[3] ; OHTANI, Yoshikazu[1] ; SHIMIZU, Akira[3]

[1] 森林総合研究所, [2] 名古屋大学地球水循環研究センター, [3] 森林総合研究所九州支所
[1]Forestry and Forest Products Research Institute, [2]Hydrospheric Atmospheric Research Center, Nagoya University, [3]Kyushu Research Center, Forestry and Forest Products Research Institute

Japanese cedar (*Cryptmeria japonica* D. Don) and Japanese cypress (*Chamaecyparis obtusa* Endl.) are the most popular planted species in Japan. These species cover about 20% of the land surface of the country. On a mountainous topography which is common in Japan, Japanese cedar was usually planted from valleys to lower hillsides with relatively wet and fertile soils, while Japanese cypress was planted on the drier and more nutrient poor ridge areas. Accordingly, evapotranspiration (ET) and carbon assimilation may be variable in the two species.

We applied multiple methods to estimate ET from a planted forest watershed located in Kyushu Island, south western part of Japan. The watershed existed on mountainous terrain, and the right bank was mainly covered with well-grown Japanese cedar while the larger part of the left bank was covered with relatively less-grown Japanese cypress. We applied the eddy covariance method, using an observation tower built in the center of the watershed. The eddy covariance data were experimentally divided to two sectors by wind direction, right bank side and left bank side of the watershed, and the lack of data for each wind sector were interpolated by the mutual imputation method. The analysis period in this study is 2007-2008. Within the period, the rainfall interception loss (I_c) and sap-flux density were also measured in Japanese cedar plots, and the lower canopy ET was estimated by a model. From the eddy covariance result, ET from the left bank side was estimated as 85% of that from the right bank side in the period. Compared the right bank side ET with the combination of I_c, upper- and lower-canopy ET, the difference in annual total ET was about 1% when global solar radiation (S_d) was greater than 0, which assured the accuracy of the eddy covariance method even over the complex terrain.

As for carbon assimilation, we simultaneously measured CO_2 flux and CO_2 concentration profile by using the observation tower. Based on the measurements, we can estimate the CO_2 exchange between the forest and atmosphere through the similar procedure to ET. Thus in this study, we will estimate the carbon budged and calculate the water use efficiency of the whole ecosystem of the watershed and of the both bank sides. From the tentative result obtained at present, the average NEE of the left bank side was 87% to that of the right bank side, in the daytime ($S_d > 0$) in 2007-2008. From the value and the aforementioned ET ratio (0.85), the water use efficiency of the both bank sides were might be almost the same as each other. In the presentation, we will discuss about the detail, considering the respired CO_2 in the nighttime and the rainfall interception in the Japanese cypress plot.

Keywords: Planted coniferous forest stand, Growth difference, Water vapor flux, Carbon dioxide flux, Water use efficiency

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乾燥熱帯域のチークプランテーションの水収支とその結果として起こる着葉期間
Water budget and the consequent canopy duration period in a teak plantation in a dry tropical region

田中 克典 [1*]
TANAKA, Katsunori[1*]

[1] 独立行政法人海洋研究開発機構
[1]Japan Agency for Marine-Earth Science and Technology

A soil-plant-air continuum multilayer model was used to numerically simulate canopy net assimilation (A_n), evapotranspiration (ET), and soil moisture in a deciduous teak plantation in a dry tropical climate of northern Thailand to examine the influence of soil drought on A_n. The timings of leaf flush and the end of the canopy duration period (CDP) were also investigated from the perspective of the temporal positive carbon gain. Two numerical experiments with different seasonal patterns of leaf area index (LAI) were carried out using above-canopy hydrometeorological data as input data. The first experiment involved seasonally varying LAI estimated based on time-series of radiative transmittance through the canopy, and the second experiment applied an annually constant LAI. The first simulation captured the measured seasonal changes in soil surface moisture; the simulated transpiration agreed with seasonal changes in heat pulse velocity, corresponding to the water use of individual trees, and the simulated An became slightly negative. However, in the second simulation, A_n became negative in the dry season because the decline in stomatal conductance due to severe soil drought limited the assimilation, and the simultaneous increase in leaf temperature increased dark respiration. Thus, these experiments revealed that the leaflessness in the dry season is reasonable for carbon gain and emphasized the unfavorable soil water status for carbon gain in the dry season. Examining the duration of positive A_n (DPA) in the second simulation showed that the start of the longest DPA (LDPA) in a year approached the timing of leaf flush in the teak plantation after the spring equinox. On the other hand, the end appeared earlier than that of all CDPs. This result is consistent with the sap flow stopping earlier than the complete leaf fall, implying that the carbon assimilation period ends before the completion of defoliation. The model sensitivity analysis in the second simulation suggests that a smaller LAI and slower maximum rate of carboxylation likely extend the LDPA because soil water from the surface to rooting depth is maintained longer at levels adequate for carbon gain by decreased canopy transpiration. The experiments also suggest that lower soil hydraulic conductivity and deeper rooting depth can postpone the end of the LDPA by increasing soil water retention and the soil water capacity, respectively. These hypotheses will be verified based on observations.

キーワード: 着葉期間, 炭素獲得, 乾燥熱帯域, 土壌-植生-大気連続系, チークプランテーション, 水収支
Keywords: canopy dyration period, carbon gain, dry tropical region, soil-plant-air continuum system, teak plantation, water budget

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AHW07-04 会場:511 時間:4 月 29 日 09:48-10:03

山地小流域における樹冠遮断が伐採後の水収支の回復に与える影響
Influence of canopy interception on the recovery in water balance after clear-cutting at a small headwater catchment

小田 智基[1*]; 江草 智弘[1]; 大手 信人[1]; 堀田 紀文[2]; 田中 延亮[3]; Green Mark[4]; 鈴木 雅一[1]
ODA, Tomoki[1*]; EGUSA, Tomohiro[1]; OHTE, Nobuhito[1]; HOTTA, Norifumi[2]; TANAKA, Nobuaki[3]; GREEN, Mark[4]; SUZUKI, Masakazu[1]

[1] 東京大学大学院農学生命科学研究科, [2] 筑波大学生命環境系, [3] 東京大学大学院生態水文学研究所, [4]Plymouth State University
[1]Graduate School of Agricultural and Life Sciences, The University of Tokyo, [2]Faculty of Life and Environmental Sciences, University of Tsukuba, [3]Ecohydrology Research Institute, The University of Tokyo Forests, Graduate School of Agricultural an, [4]Center for the Environment, Plymouth State University

The impact of forest disturbance on stream runoff has been well studied using the paired catchment approach, usually finding increased stream runoff following forest disturbance due to the decline of transpiration and canopy interception. However the recovery processes of transpiration and interception have rarely been directly observed under a recovering forest, therefore mechanisms behind recovery time of stream runoff following forest cutting is still not well understood. The objective of this study is to evaluate the contribution of interception to the change of stream runoff after forest cutting. This study was conducted in a pair of small headwater catchments, where one catchment was clear-cut in 1999 and planted with the same species in 2000. Annual runoff increased 200 to 300 mm/yr after forest cutting and the higher runoff remains 12 years after cutting. Interception ratio in the clear-cut catchment were lower than 10 % of precipitation in 2007, 2011 and 2012, and those in the control catchment were 20 to 24 % of precipitation. The mean annual interception was still around 300 mm/yr smaller in the young forest compared to the mature forest, although canopy cover and LAI were similar. These results suggested that the recovery of interception rate is an important controlling factor for the recovery of stream runoff after forest cutting, and not only canopy structure, but also the microclimate condition above the canopy of young forest could be also important factors affecting interception.
Keywords: forest cutting, water balance, canopy interception, headwater catchment

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針広混交林流域における水流出の年々変動
Changes in interannual variability of runoff in a conifer and deciduous hardwood mixed forested watershed

野口 正二[1*] ; 村上 亘[1] ; 谷 誠[2]
NOGUCHI, Shoji[1*] ; MURAKAMI, Wataru[1] ; TANI, Makoto[2]

[1] 森林総合研究所, [2] 京都大学農学研究科
[1]Forestry and Forest Product Research Institute, [2]Graduate School of Agriculture, Kyoto University

The National Forest Management conducts forest management in National Forests for the fulfillment of multi functional roles of forest including long-term wood production management. On the other hand, there are few studies that evaluated the runoff characteristics including a state of the forest for a long term. This study was conducted within the Kamabuchi No1 experimental watershed (3.06ha) in North part of Japan. Hydrological observation has been continued in cold snowy region since 1939. It is the longest record in this region in Japan. The site is covered with Natural hardwood forest (ex. Fagus crenata, Quercus mongolica var. grosseserrata and Quercus serrata) and coniferous plantation forest (Cryptomeria japonica and Chamaecyparis obtuse) which planted around 1912 to 1916. Surficial geology is tuff and shaletic tuff of the Tertiary period and soils are clay loam. Meteorological observation was conducted Yamagata experimental forests located to 800m from the watershed to the northeast. A 71-year record (1939-2010) of the precipitation and runoff was used for an analysis of the flow-duration curve. Tree (DBH ≥ 6cm) census in the watershed was also conducted at 5 times (1942, 1950, 1957, 1979, 2008). The tree volume of Chamaecyparis obtuse is a regular tendency and the tree volume of Cryptomeria japonica linearly increased. Stem volume of oak trees has increased remarkably from 1942 to 1979 but there was a close tendency of an increase in 2008 because mortality of oak trees occurred in the watershed. Based on 5 times tree census, positive linear relationship was found between tree volume and age of stand. While the proportion of plentiful runoff has shown a tendency to decrease over long term, those of ordinary, low and scanty runoffs have tended to increase with increasing the tree volume.

キーワード: 長期水文観測, 積雪寒冷地域, 流況曲線, 流出特性
Keywords: duration curve, cold snowy region, long term hydrological observation, runoff characteristics

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AHW07-06 会場:511 時間:4 月 29 日 10:18-10:33

山地流域の降雨流出応答に一般則はあるか？
Is there any general rainfall-runoff response function in mountainous catchments?

内田 太郎 [1*] ; 浅野 友子 [2] ; 蒲原 潤一 [1] ; 友村 光秀 [3]
UCHIDA, Taro[1*] ; ASANO, Yuko[2] ; KANBARA, Jun'ichi[1] ; TOMOMURA, Mitsuhidde[3]

[1] 国土技術政策総合研究所, [2] 東京大学, [3] 気象工学研究所
[1]National Institute for Land and Infrastructure Management, [2]University of Tokyo, [3]Meteorological Engnieering Center

Clarifying rainfall-runoff response function in mountainous catchments is one of key issues for flood and sediment disaster prediction, management of aquatic environment, water supply and so on. So, rainfall-runoff response function in mountainous catchments has been debated in more than several decades. A variety of studies, observation, modeling, theoretical studies etc., has been conducted. Many noble efforts have been conducted for clarifying complex systems in catchment hydrology through intensive observations. These observations were effective for documentation of the idiosyncrasies of each catchment environments. However, it has been difficult to derive general rainfall-runoff response function from these basin-centric approaches. So, several researchers emphasized the importance of intercomparison so as to better see first order controls of hydrologic responses. Except for several exceptions, intercomparisons for rainfall-runoff responses in many catchments are still limited. Thus, still it is very hard to predict rainfall-runoff response function at ungauged basin.

Thus, we compiled rainfall and stream flow data for around 150 catchments in Japan. We focused relatively small catchment (<100 km2) and a variety of geological, topographical and climatic conditions. We removed catchments where strongly affected human activities, such as urbanized catchment etc., from our intercomparison.

In this study, we randomly sampled 10 storms, i.e., total rainfall amounts were large than 50 mm, for each catchment and calculated three indices, peak specific discharge, peak lag time and direct runoff ratio, to characterize rainfall-runoff response. Also, we defined rainfall-runoff responses using three reservoirs model. We parameterized all of catchments using four storms data using SCE-UA method and validated these parameters using other four storms data. Then, we tested the roles of rainfall condition, climate, geology and topography on rainfall-runoff responses. We used multiple regression analysis to define first order controls of rainfall-runoff responses.

We found large variability in rainfall-runoff responses and it is hard to define general response patterns. While, through multiple regression analysis, we found several interesting results, as follow;

-Climatic conditions affected peak specific discharge and direct runoff ratio, suggesting that climate might give impacts on hydrological characteristics soil and bedrock.

-Geology, such as type of rocks and geological age, gave impacts on rainfall-runoff responses, but effects of geology were not so large, although many study focused on rock-controls on hydrology.

-Flowpath length, calculated by DEM, was one of important topographic parameters for describing rainfall-runoff responses.

キーワード: 山地流域, 降雨流出応答, データベース, 多変量解析
Keywords: headwater catchment, rainfall-runoff response, database, multiple regression analysis

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斜面・河道発達過程を導入した模擬流域発生手法
A method of generating virtual drainage-basin by introducing models of slope/stream evolution

中北 英一 [1*]
NAKAKITA, Eiichi[1*]

[1] 中北英一
[1]Eiichi Nakakita

A method of generating virtual drainage basin to understand relationship among characteristics of geomorphic distribution, rainfall distribution, and runoff distribution was developed. Here the concept of generating virtual drainage-basin is that the drainage-basins are generated at random under some physically based conditions on the basin form. The method is an improvement of Nakakita and Matsuda (2007). They proposed the method of generating virtual drainage-basin based on erosional developing model of channel network by Horton (1945). For the improvement, mathematical models of evolution of slopes and streams were introduced into the methodology. As a result, we achieved to introduce the concept of time into the generating virtual drainage-basin model.
Keywords: drainage basin, landform evolution, channel network, slope evolution, longitudinal profile

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湿潤温暖地域におけるロックコントロールおよびはげ山と浸透水の排水システム
Rock control, denuded hillslope and discharge system in warm humid regions

飯田 智之 [1*]
IIDA, Tomoyuki[1*]

[1] 筑波大学アイソトープ環境動態研究センター
[1]Center for Research in Isotopes and Environmental Dynamics, University of Tsukuba

日本のような湿潤で温暖な気候下では、地形や地盤（土層・風化層）だけでなく、植生特に樹木が重要な役割を果たすことで、豪雨時の安定的な排水システムが維持されている。長期的に見た場合、そこでは、地形・地盤・樹木・浸透水がそれぞれ直接的・間接的に水文地形学的な相互作用を及ぼしあっている。

排水システムの中で、透水性と保水性を支配する地盤の大小の間隙は特に重要である。洪水時に重力水の主要な排水ルートとなる水みち（パイプ）は、連続した大間隙である。また、小間隙に保持されていた毛管水は、無降雨時に樹木の成長に利用される。このような大小の間隙や水みちの生成には、物理的風化作用や化学的風化作用よりも、むしろ生物的風化作用が大きく寄与している。すなわち、樹木をはじめとする植生や地中の小動物は、それぞれの生活に快適な環境をみずから実現することで、無機的で硬い土層を有機的で軟らかい山地土壌へと変化させている。

安定した排水システムは生物にとって快適な環境のひとつと推定されるが、降雨条件によって以下のように変化する。

１） 通常の豪雨時：排水システムは安定しており、降雨を浸透水に変換してスムーズに系外へと排水する。

２） 異常な豪雨時：地下水位上昇や水みち閉塞に伴う間隙水圧上昇により斜面崩壊が発生して、排水システムが部分的に破壊される。しかし、その後長い時間をかけて植生や土層が回復することで、排水システムも徐々に回復する。これは正のフィードバックと呼ぶことができる。この植生や土層の回復には、植生の生育に適した湿潤温暖気候が大きく寄与している。そのため、自然のままでは、崩壊面が拡大して山地が全面的に裸地化することはない。

３）森林破壊後の異常な豪雨時：人間により、森林伐採だけでなく、根株の掘り起こしなど、樹木の根茎まで収奪して、土層全体を撹乱するような徹底した森林破壊がなされた場合には、花崗岩や第三紀層など地質によっては、正のフィードバック作用の臨界点を超えて負のフィードバック作用が働くようになる。その結果、山地の裸地化が一方的に進行し、もはや自然の作用では植生や土層が回復することができなくなる。これが、20 世紀後半の比較的最近まで、日本各地で見られた“はげ山”である。そこでは、当然安定した排水システムも無くなるので、豪雨時には表面流が増加することで洪水が頻発して土砂流出も激しくなる。森林からはげ山、あるいは、はげ山から森林への過渡的状況では、斜面崩壊が多発する。

以上のような、降雨の排水システムは、水文地形学的な斜面発達の一環として形成されるが、それには基盤岩の地質が大きく影響しており、地質ごとに独自の排水システムが形成されると推定される。一種のロックコントロールである。

そのような観点から、本研究では、花崗岩と花崗せん緑岩という対称的な２種類の地質からなる山地における、風化・斜面崩壊・はげ山・地形変化と排水システムの相互作用について比較検討する。

キーワード: 浸透水, 排水システム, ロックコントロール, はげ山, 地盤構造, 水文地形学的相互作用
Keywords: hillslope hydrogy, discharge system, rock control, bare land, ground structure, hydro-geomorphological interaction

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AHW07-09 会場:511 時間:4 月 29 日 11:36-11:51

毎木調査による崩壊防止力二次元分布図の作成法
The making method of two dimensional distribution map of the collapse prevention force with tree survey

阿辻 雅言 [1*] ; 北原 曜 [2] ; 小野 裕 [2]
ATSUJI, Makoto[1*] ; KITAHARA, Hikaru[2] ; ONO, Hiroshi[2]

[1] 信州大学大学院農学研究科, [2] 信州大学大学院農学部
[1]Graduate School of Agriculture, Shinshu University, [2]Faculty of Agriculture, Shinshu University

森林根系の崩壊防止力は土層の鉛直断面 1m^2 あたりの引き抜き抵抗力の総和である。このうち引き抜き抵抗力は，根系直系の 1.6 乗程度に比例し，その係数は樹種により異なる。一方，根系量は立木中心から同心円状に分布し，立木からの距離に対して指数関数的に減少する。

ここでは，この引き抜き抵抗力と根系分布から，地下を掘削することなく毎木調査による地上の情報から崩壊防止力の二次元分布図を作成したことを報告する。調査はヒノキ人工林 3 林分と広葉樹天然林 1 林分にてそれぞれ行い，毎木調査により得た立木位置と胸高直径のデータから崩壊防止力二次元分布図を作成し，検証のためにトレンチを掘削して計測した崩壊防止力と比較した。その結果，実測値と推定値は一致しなかったものの，両者の間には危険率 1%で有意な関係が見られた。

さらに，この手法を応用して崩壊防止力の時系列変化を推定した。崩壊防止力推定に必要なデータは立木位置と胸高直径のみであるため，密度管理曲線による成長予測と併せて用いることで間伐後の崩壊防止力変化なども推定できる。

キーワード: 根系, 崩壊防止力, 人工林, 天然林, 二次元分布図
Keywords: root system, collapse prevention forse, artificial plantation, natural forest, two dimensional distribution map

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AHW07-10 会場:511 時間:4 月 29 日 11:51-12:06

地形・土壌・植生の発達・崩壊シミュレーション手法
The growth-collapse simulation method of soil depth in which the effect of vegetation was taken into consideration

黒川 潮 [1*]
KUROKAWA, Ushio[1*]

[1] 森林総合研究所九州支所
[1]Kyushu Research Center, FFPRI

The impact accompanying the transition of the watershed conditions in a forest appears under the structurally development process of a triplex in which time scales differ; geographical feature is formed by a tubercle and erosion of a mountain, the soil which supports and grows up in the root system of a vegetation repeats a collapse and a renature, the forest grows and withers. Without understanding this process, the runoff impact evaluation of watershed conditions cannot occur. We paid our attention to the collapse process in which a soil grows up again, after the soil was supported by the root of the forest, grew up and collapsed with progress of a temporal. And the development method of the longterm soil growth simulation was considered.

This method is computed for every mesh. The following routines perform the compute process of geomorphic development. First, the amount of growths of the soil stratum in the fixed period in each mesh is computed. The amount of developments of the soil depth used the equation of the following which Heimsath et al. (1999) proposed.

Soil Production(m/million year)=77×exp(-0.024×Soil Depth)

The soil depth after a fixed period is computed by applying to the initial soil depth of each mesh the value calculated by the equation. Slope stability is computed using the soil depth set up newly. It is considered by the equation that the mesh by which the safety factor was computed or less with one is that to which the collapse occurred. After setting the value of the soil depth in the mesh to 0, the altitude data after a collapse and a soil depth are re-calculated. A prolonged soil development simulation is computed by repeating the predetermined number of these processes. The simulation was computed at the place which many shallow landslides caused by heavy rainfall. The initial soil depth in the mesh which the collapse caused by the heavy rain was set to 0, and the mesh which has not collapsed was set to 1 m. And, the soil layer assumed the condition of being completely saturated by the heavy rain. In addition, the effective soil internal angle was 32 degrees, effective soil cohesion was 0.01 kPa, unit weight of the moist soil was 17.64 kN/m^3, and unit weight of water was 9.8 kN/m^3. The effect of the vegetation was included in the simulation as the cohesion.

As results of the simulation, It was confirmed that the soil layer which collapsed with progress of the temporal is recovered. Moreover, when a vegetation does not exist, the probability that a soil layer will repeat a collapse becomes high, but when a vegetation exists, a soil layer does not collapse but is recovered early.
Keywords: soil depth, geographical feature, vegetation, simulation method

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AHW07-11 会場:511 時間:4 月 29 日 12:06-12:30

Limits of Soil Production and the Couplings with Hillslope Hydrology
Limits of Soil Production and the Couplings with Hillslope Hydrology

HEIMSATH, Arjun[1*]
HEIMSATH, Arjun[1*]

[1]School of Earth and Space Exploration, Arizona State University
[1]School of Earth and Space Exploration, Arizona State University

Rocky mountain ranges are broken down to sediment that is ultimately removed to the sea. Tectonic forces continually push mountains up, while physical and chemical processes continually transform bedrock to sediment and move it down. This simple sounding cycle is thought to regulate global climate over long timescales, while also responding to climate forcing itself, although the causal direction remain a mystery despite decades of sleuthing. Similarly mysterious are the connections between mechanisms of sediment production and the responses of watersheds to changes driven by humans, climate, or tectonics.

To address some of the potential connections between sediment production and hillslope hydrology, I focus here on soil mantled and steeply sloped landscapes from around the world, some thought to be at a critical threshold of soil cover. Observations reveal that even in the most rapidly eroding landscape there are significant areas mantled with soil that fit the conceptual framework of a physically mobile layer derived from the underlying parent material with some locally-derived organic content. The extent and persistence of such soils depends on the long-term balance between soil production and erosion despite the perceived discrepancy between high erosion and low soil production rates. I present cosmogenic Be-10-derived soil production and erosion rates that show that soil production increases with catchment-averaged erosion, suggesting a feedback that enhances soil-cover persistence, even in threshold landscapes. I also show that a process transistion to landslide-dominated erosion results in thinner, patchier soils and rockier topography, but find that there is no sudden transition to bedrock landscapes. The landslide modeling is combined with a detailed quantification of bedrock exposure for these steep, mountainous landscapes.

To conclude, I draw an important conclusion connecting the physical processes producing and transporting soil and the chemical processes weathering the parent material by measuring parent material strength across three different field settings. Parent material strength is observed to increase with overlying soil thickness and, therefore, the weathered extent of the saprolite. Soil production rates, thus, decrease with increasing parent material competence. These observation highlight the importance of quantifying hillslope hydrologic processes where such multi-facted measurements are made.

キーワード: Soil erosion, Soil production, Critical Zone, Weathering, Hillslope hydrology, Saprolite
Keywords: Soil erosion, Soil production, Critical Zone, Weathering, Hillslope hydrology, Saprolite

Japan Geoscience Union Meeting 2014
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AHW07-12 会場:511 時間:4 月 29 日 12:30-12:45

日本の花崗岩山地流域における土層形成速度関数と土層輸送係数: 豪雨による表層崩壊の水文地形学的危険度評価にむけて
Soil production functions and soil layer mobility in Japanese mountainous catchments underlain by granitoid rocks

松四 雄騎 [1*] ; 松崎 浩之 [2]
MATSUSHI, Yuki[1*] ; MATSUZAKI, Hiroyuki[2]

[1] 京都大学防災研究所地盤災害研究部門, [2] 東京大学大学院工学系研究科
[1]DPRI, Kyoto University, [2]MALT, The University of Tokyo

Soil-mantled hillslopes cover a major area of mountainous catchments in humid temperate regions. The soil layer on hillslopes is maintained by a balance between soil production and transport especially at hill noses, while the soil accumulated in hollows is eventually removed by a rainfall-induced shallow landslide. The rates of soil production and soil creep pace the growth of soil thickness at a hollow and thus determine the return period of landsliding. The soil layer buffers rainfall infiltration into hillslopes and hence controls subsurface runoff system in a catchment. Hydro-geomorphological evolution of a catchment results from the interaction between long-term soil layer development and short-term rainfall runoff processes. The quantification of soil dynamics on hillslopes is thus critical in understanding present-day hydrological condition of a catchment and for geomorphological landslide hazard mitigation.

The uppermost part of decomposed bedrock (saprolite) gradually disintegrates to form the mobile soil layer, which achieves to a steady-state thickness reflecting sediment budget at a soil column. The saprolite-to-soil conversion rate beneath a soil column decreases with increasing thickness of the soil layer, which is called as soil production function (SPF). Soil particles apart from the saprolite move downslope by soil creep at a rate controlled by slope gradient, biological activity and soil thickness. Evaluation of SPF as well as the soil layer mobility is essential when we simulate soil dynamics on a hillslope. SPF can be determined from concentration of terrestrial cosmogenic nuclides at uppermost part of saprolite, while soil layer mobility can be estimated by soil thickness survey by digging pits on a nose-hollow pair of hillslopes. We present examples of SPFs in Japanese mountainous catchment underlain by granitic rocks, and demonstrate results of simulation of soil development to map potential sites of shallow landslide and to assess volume of sediment that may yield at a catastrophic landslide event by heavy rainfall.

キーワード: 土層形成速度関数, 宇宙線生成核種, 土砂輸送, 表層崩壊, 地形発達
Keywords: soil production function, terrestrial cosmogenic nuclides, sediment transport, shallow landslide, landscape evolution

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AHW07-13 会場:511 時間:4 月 29 日 14:15-14:30

古生層堆積岩流域における山地斜面土壌水分と渓流水量の連動性
Interrelation between hillslope soil moisture and stream flow in a Paleozoic sedimentary rock watershed

細田 育広 [1*]
HOSODA, Ikuhiro[1*]

[1] 森林総合研究所関西支所
[1]Kansai Research Center, FFPRI

It is well known that geology is one of influential factors on river regime. In the Paleozoic sedimentary rocks area in Japan, hydrographs are characterized by low base flow and spiky peak flow. To clarify the reasons of such characteristics occur, observation focused on hillslope soil moisture condition was conducted in the gauged Tatsunokuchi-yama Minami-tani watershed (34 ^{0} 42' N, 133 ^{0} 58' E, 50-257 m, 23 ha) underlain by Paleozoic sedimentary rocks. The watershed is covered with primarily *Quercus serrata* dominant mixed forest, and partly *Chamaecyparis obtusa* stands planted in 1970s. Annual precipitation is about 1200 mm with little snowfall.

Ground water levels (GWL) and soil moisture were continuously measured in and around boreholes in a concave slope in the middle reach. Deeper than 0.3 m from ground surface, a thick fractured and weathered bed rock layer extends down to about 10 m at upper slope, and about 16 m at mid-slope. Below the weathered bed rock layer, boring core was relatively unweathered. But conspicuous cracks were obviously seemed to perform as water flow pathway because the surface of crack was dyed. Low coefficients of permeability which ranged from 2^{-8} to 1^{-6} m/s were measured by in situ test in the boreholes.

In the mid-slope, GWL appeared about 15 to 17.5 m in depth from ground surface when surface soil layer was more than field moisture capacity. Although GWL greatly respond to about over 40 mm rainfall events, direct flow rate did not simply increased. In a little antecedent rainfall condition, GWL rising was detected only at the lower slope. Depending on increase of antecedent rainfall, fluctuations of GWL at the mid-slope and the upper slope became obvious, and also direct flow rate went up. The greater amount of rainfall including antecedent rainfall was brought, the more GWL rising belated to stream flow peak observed. The greater intensity of rainfall leads quick rising of stream flow, but it was not effective for GWL rising. According to the stream water quality, rain water component increased when intense rain was brought, subsequently ground water component increased for the duration of rainfall event.

It is realized that water movement is having macroscopic interrelation in the space from upper slope to stream channel. Its complexity would be derived from large soil moisture change by rainfall amount and vegetation activity in the thick weathered bed rock layer in the hillslope as water flow pathways. And it is considered that since the permeability of subsoil is low, stream flow respond by spiky peak against intense rainfall.

キーワード: 透水性, 土壌 pF, 地下水, 瀬戸内海式気候, 竜ノ口山
Keywords: permeability, soil water pF, ground water, Seto inland sea climate, Tatsunokuchi-yama

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AHW07-14 会場:511 時間:4 月 29 日 14:30-14:45

風化花崗岩山地における基岩地下水の水質特性
Variability of the chemistry of streamwater and bedrock groundwater at a weathered granite mountain, Japan

藤本 将光 [1*] ; 小杉 賢一朗 [2] ; 正岡 直也 [2] ; 馬場 直輝 [1] ; 上田 竜也 [1] ; 酒井 康祐 [1] ; 深川 良一 [2] ; 谷 誠 [1]
FUJIMOTO, Masamitsu[1*] ; KOSUGI, Ken'ichirou[2] ; MASAOKA, Naoya[2] ; BANBA, Naoki[1] ; UEDA, Ryuya[1] ; SAKAI, Yasuhiro[1] ; FUKAGAWA, Ryouichi[2] ; TANI, Makoto[1]

[1] 立命館大学, [2] 京都大学
[1]Ritsumeikan University, [2]Kyoto University

Introduction

Previous studies have noted that bedrock groundwater is one of the important factors influencing stream discharge and streamwater chemistry. However, most previous studies were conducted not by direct measurement of bedrock groundwater but by using indirect methods, such as solute tracers and water budget analysis. Thus, the movement and chemical characteristics of bedrock groundwater remain incompletely understood based on direct measurements of bedrock groundwater. To better understand the dynamics of bedrock groundwater, we investigated groundwater table movement and water chemistry of bedrock groundwater using dense borehole wells at a small catchment in a mountainous area.

Methods

The study was performed at the Fudoji Experimental Watershed located in the Tanakami Mountains in the southeastern part of Shiga Prefecture, central Japan. Precipitation was monitored using tipping-bucket rain gauges, and discharges were observed at eight small catchments, ranging in area from 0.1 to 2.3 ha. Seven small catchments (subcatchments) were included in the largest catchment (2.3 ha), within which we installed 61 borehole wells. The water table of bedrock groundwater was then observed at these borehole wells. Rainwater, streamwater from the small catchments and bedrock groundwater from the borehole wells were sampled, and the concentrations of major ions and SiO_2 as well as the water stable-isotope ratios $d^{18}O$ and dD were measured in the Graduate School of Agriculture, Kyoto University.

Results and Discussion

The results of the analysis of the groundwater table of bedrock groundwater indicated that there were several fluctuating characteristics and that these characteristics of groundwater table change had locality. At the area having higher altitude in the ridge, the bedrock groundwater-table changes were gradual but the ranges of fluctuation were larger than those of the lower wells. At the lower-altitude points, although the bedrock groundwater table responded rapidly, the ranges of fluctuation of the groundwater table were small relative to those of the higher points. Some areas responded only to peak rainfall over a short time. Based on the groundwater flux analysis, bedrock groundwater moves across the surface divide. A catchment inflowed by a neighboring catchment showed a high specific discharge. Additionally, the direction of groundwater movement changed during rainfall events, and such changes were similar for rainfall events of the same size.

The relationships among chemistries derived from the chemical weathering of bedrock indicated that although the weathering processes were similar in the catchment, the weathering level varied among the borehole wells. The chemistries of bedrock groundwater at each catchment and of streamwater at each catchment showed large variability. The concentrations of Na^+ and Ca^{2+} had local characteristics, but no clear characteristics were observed among other bedrock groundwater components. The chemical concentrations of bedrock groundwater were higher than those of streamwater. We chose borehole wells that may contribute directly to the stream based on the direction of groundwater movement by an analysis of groundwater flux and distance from the borehole wells, and noticed that there were also large gaps between the chemistries of streamwater and bedrock groundwater. These results indicate that complex processes of chemical dynamics occur in the weathered bedrock and from the weathered bedrock to the stream.

キーワード: 風化基岩, 高密度ボーリング孔, 水質分布, 基岩地下水
Keywords: weatherd bedrock, densely bore holes, chemical variability, bedrock groundwater

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AHW07-15 会場:511 時間:4 月 29 日 14:45-15:00

風化花崗岩山地における平均滞留時間から見た基岩内地下水動態
Mean residence time and hydrochemistry of bedrock groundwater aquifer in a Granite mountain

勝山 正則[1*] ; 小杉 賢一朗[2] ; 谷 誠[2]
KATSUYAMA, Masanori[1*] ; KOSUGI, Ken'ichiro[2] ; TANI, Makoto[2]

[1] 京都大学学際融合教育研究推進センター, [2] 京都大学農学研究科
[1]Center for the Promotion of Interdisciplinary Education and Research, Kyoto University, [2]Graduate School of Agriculture, Kyoto University

Bedrock groundwater dynamics is one of the latest frontier of hillslope- and catchment hydrology. Although it relate to water resources as well as sediment disasters, only few studies have accessed directly with boreholes to bedrock groundwater aquifer because of, for example, high costs. In this context, tracer approach is effective to clarify the bedrock groundwater dynamics and water pathways within deeper layers of mountains. We have been keeping on monitoring of the chemical and isotopic compositions of bedrock groundwater and streamwater in Kiryu Experimental Watershed (KEW), Japan since 2003. We set up a nested observation system; a hillslope plot (AP, 0.024ha), a subcatchment (A catchment, 0.086ha), and whole of KEW (K catchment, 5.99ha), and monthly sampled the streamwater of K and A, the outflow from AP, which occurs as saturated throughflow on the soil-bedrock interface during rainstorms, and groundwater in the soil sediment. Moreover, we excavated the bedrock and installed some tension lysimeters at 0.1, 0.2, 0.4, and 0.8 m deep and boreholes at 12, 15, and 20 m deep below bedrock surface, and sampled them. The stream flow from K and A were perennial. The SiO2 and Na+ concentrations increased along with the infiltration process. On the other hand, the NO3- concentration was highest at the surface soil water, and removed along with the infiltration process. The concentrations of both solutes in the streamwater from A and K were intermediate between the concentrations in the surface soil water and bedrock groundwater. These facts mean that the streamwater is the mixture of shallow soil water and deep groundwater. The mean residence times calculated by delta 18O variations were about 4 or 5 months in the groundwater in the soil sediment and in the shallow (<0.8m) bedrock groundwaters, about 50 months in 12- and 15 m deep, and about 120 months in 20 m deep, respectively. That in the streamwater in A was estimated as about 30 months. Thus, the MRT in 20 m deep groundwater is quite different from the others. The relationship between the MRTs and the solute concentrations were different in each solute; for SiO2, the concentration increased as a saturation curve, and it increased as linearly for Na+. It exponentially decreased for NO3-. The streamwater chemistries in A were on these curves. Therefore, the solute concentrations can be described as functions of MRTs. These results suggest that a part of the bedrock groundwater can contribute to the stream from the shallower layers. The fact that the stream flow is perennial in this subcatchment A means that plentiful supply of groundwater from the relatively shallow bedrock layers exist. On the other hand, other part of the bedrock groundwater infiltrate deeply and less contribute to the stream in this small subcatchment; we have to consider whether the deeply infiltrated groundwater may contribute at the outlet of K catchment. Moreover, as the deeper bedrock groundwater have especially long residence time, we have to keep long-term monitoring to understand the dynamics and roles of this groundwater to hydrological and hydrochemical processes, because it will be a key of spatio-temporal scaling of these processes, as well as the water yield function of forests.
Keywords: Bedrock groundwater, Tracer, Mean residence time, granite catchment

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AHW07-16 会場:511 時間:4 月 29 日 15:00-15:24

Hydrological change at the catchment scale: The need to address both velocity and celerity

Hydrological change at the catchment scale: The need to address both velocity and celerity

MCDONNELL, Jeffrey[1*]
MCDONNELL, Jeffrey[1*]

[1]Global Institute for Water Security, University of Saskatchewan CANADA
[1]Global Institute for Water Security, University of Saskatchewan CANADA

Water quantity and quality response to climate- and land use change are difficult to predict. Much of this relates to the complexities of water flow paths and our inability to relate measureable catchment properties to measureable hydrologic response metrics. To date, most work has focused on rainfall-runoff response — that is, the celerity component of change. Here I present new work from 15 headwater catchments, (0.1 to 100 km^2) in the Oregon Cascades and Oregon Coast Range in the USA, aimed at quantifying both celerity and flow velocities (i.e. particle transport through the system). I illustrate this velocity component through stable isotope analysis of runoff components and the mean transit time and residence time analysis of surface water and groundwater, respectively. Results show that despite very similar rainfall-runoff determined celerities, these systems have distinctly different tracer velocities, where transit time of headwater streamflow is 1-3 years in the catchments draining the Western Cascade mountains and 3-11 years in the streams draining the Coast Range mountains. More importantly, the scaling of surface water mean residence time in the Cascades is linked to internal topographic structure of individual sub-catchments whereas Coast Range sites show no evidence of this; and streamwater residence times scale linearly with catchment area. I discuss the implications of these celerity-velocity differences for catchment-scale climate- and landuse change effects in the USA Pacific Northwest and for more general efforts like the IAHS Panta Rhei initiative.

キーワード: Hillslope, Rainfall-runoff, Stable isotope, Climate change, Landuse, Groundwater
Keywords: Hillslope, Rainfall-runoff, Stable isotope, Climate change, Landuse, Groundwater

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AHW07-17 会場:511 時間:4 月 29 日 15:24-15:39

急峻なゼロ次谷流域における洪水流出過程と侵食過程の相互因果関係の理解に向けて
Toward understanding causal interrelationships between stormflow and erosion processes in a steep zero-order basin

谷 誠[1*]
TANI, Makoto[1*]

[1] 京都大学農学研究科
[1]Graduate School of Agriculture, Kyoto University

ゼロ次谷における洪水流出発生と土壌浸食過程は、時間スケールがはるかに異なるにもかかわらず、密接な相互依存性がある。本研究は、洪水流と浸食過程の相互依存性に関して、ゼロ次谷内部の尾根筋と谷筋における相違点があることに注目する。

さて、地殻変動帯における強い侵食力によって流域全体で重力による土壌移動が進行するが、尾根筋では、土壌移動が拡散的で緩慢であるため、基岩表面の地形の凹凸によって土壌の厚さがきまる傾向がある (Heimsath, Geomorphology 27, 1999)。一方、谷筋では、土壌層が突発的な表層崩壊で失われるわけであり、崩壊が起こらない限り、10^2 から 10^4 年の長い時間スケールで土壌層が発達してゆく (Tsukamoto et al., IAHS Publ. 137, 1982)。そのため、尾根筋では、土壌層は植生を攪乱なく乗せたまま移動してゆくのだが、その尾根筋からの拡散的な土壌供給によって、谷筋の表層崩壊後における土壌層の回復が支えられている。したがって、尾根筋の拡散過程と谷筋の土壌層回復過程は密接な相互関係を持つとみられる。

こうした過程が進行するためには、尾根筋であれ谷筋であれ、表層崩壊のきかっけとなる飽和地表面流は抑制されていなければならない。この抑制に対しては、パイプ状の水みちを通じた排水能力 (McDonnell, Water Resour. Res. 26, 1990) が大きな役割を果たしているとみなされる。

ここでは、この考え方を水文学的に考察するため、小流域における降雨流出応答関係から、洪水流発生寄与域の拡大を推定する解析を試みる。降雨がほとんどすべて洪水流になるような湿潤な条件では、準定常状態であるような水理学的連続体が形成され、一段タンクモデルによって、洪水流出応答が良く再現されることがわかっている (Tani: Hydrol. Earth Syst. Sci., 17, 2013)。こうした単純な応答特性を利用すると、洪水流出寄与域の拡大状況が流出応答から逆推定可能というわけである。

その解析を行った結果、乾燥状態が残る降雨初期の短い期間を除き、洪水時の降雨流出の波形変換は、一段タンクモデルの同一のパラメータで良く再現され、流出寄与域のみが増加することがわかった。この結果は、波形変換が主に斜面方向の地中流や地表面流で起こるのではなく、鉛直方向の水移動に由来していることを推定させる。こうした流出メカニズムの概念モデルはすでに指摘されているところであって (Montgomery and Dietrich, Water Resour. Res. 38, 2002)、パイプ状水みちの大きな排水能力によって雨水が土壌層内に閉じ込められることを示唆している。この閉じ込めによって、尾根筋はもとより谷筋において、強い侵食力に抗して土壌層が発達できる環境が創り出されているわけである。

流出過程と侵食過程は強く結びついており、その観測による裏づけが今後重要になる。加えて、既存の水文データからも、こうした結びつきの観点から解析することによって、興味深い知見が得られると考えている。

キーワード: 侵食, 斜面水文学, 土壌層発達, 洪水流, 寄与域変動, ゼロ次谷流域
Keywords: erosion, hillslope hydrology, soil-layer evolution, stormflow, variable contribution area, zero-order basin

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山地源流域における基岩地下水と表層水文プロセス・地形形成プロセスとの相互作用
Interaction between bedrock groundwater and surface-hydrological and geomorphological processes in mountainous headwater

小杉 賢一朗[1*] ; 藤本 将光[2] ; 山川 陽祐[3] ; 正岡 直也[1] ; 糸数 哲[1]
KOSUGI, Ken'ichirou[1*] ; FUJIMOTO, Masamitsu[2] ; YAMAKAWA, Yosuke[3] ; MASAOKA, Naoya[1] ; ITOKAZU, Tetsushi[1]

[1] 京都大学, [2] 立命館大学, [3] 筑波大学
[1]Kyoto Univ., [2]Ritsumeikan Univ., [3]Tsukuba Univ.

Enormous landslides with deep slipping surfaces, which are likely to be triggered by the huge storms expected with climate change, can be one of the major geomorphological processes in the temperate climate zone. This study focuses on groundwater in mountainous headwater regions as a potential cause of such landslides. Recent hydrological studies have revealed that large amounts of rainwater infiltrate into bedrock, suggesting the possibility that steep mountains could contain greater amounts of groundwater than previously thought. The decline in groundwater levels due to water harvesting should be effective for the prevention of landslides. At the same time, the exploitation of groundwater resources in mountainous regions may contribute to establish a sustainable supply of safe water; that is, groundwater in mountainous regions is of better quality and less vulnerable to pollution because human activities are limited in the source areas. Thus, the exploitation of groundwater resources in mountainous regions should produce a win?win situation that achieves both disaster mitigation and a sustainable water supply. This study investigates hydrological methods for observing and analyzing quantitative and qualitative signals in mountain streams that can be used for detecting groundwater dynamics in steep mountains. Such hydrological methods are effectively combined with geophysical surveys.

In the steep Rokko mountain range of central Japan, which consists of granite and has been greatly affected by diastrophic activities, discharge hydrographs are characterized by significant amount of baseflow. In order to elucidate contributions of bedrock groundwater to the hydrograph formation, long-term hydrological observations were conducted by using bedrock wells with depths of 7-78 m drilled at 31 points within a 2.1-ha headwater catchment in the Rokko mountain range. Results indicated a fairly regionalized distribution of bedrock groundwater; that is, upper, middle, and lower aquifers were present. We observed large differences in water level among the aquifers, instead of a gradual and continuous decline in water level. Discharge hydrograph from the catchment was notably characterized by gentle and significant variations in base flow and exhibited triple-peak responses. Flashy first peaks occurred just after rainfall peaks, while the second peaks lagged behind the rainfall peaks by a few days. Broad peaks in the base-flow discharge corresponded to the third peaks, which occurred once or twice in each hydrological year. The triple-peak discharge responses were explained by three types of water pathways: the first peak was caused by the peak in soil mantle groundwater around the outlet of the watershed; the second peak was caused by the first peak in the lower aquifer, which was fed by vertical rainwater infiltration; and the third peak was caused by the second peak in the lower aquifer, resulting from an increased lateral water supply from the middle aquifer. The middle aquifer was recharged by vertical infiltration through weathered bedrock and lateral flow from the upper aquifer. Because of its broad regional expanse and large capacity, the middle aquifer had a dominant effect on formation of the discharge hydrograph. Thus, this study has demonstrated how discharge from the steep headwater catchment is dominated by complex flow systems within bedrock groundwater; the spatial expanse of bedrock aquifers and interaction among aquifers are key factors.

キーワード: 大崩壊, 地形形成, 源流域, 基岩地下水, 水資源
Keywords: enormous landslide, geomorphological processes, headwater catchment, bedrock groundwater, water resources