UNIVERSIDADE FEDERAL DE LAVRAS

LEANDRO CAMPOS PINTO

HYDROPEDOLOGY AT THE MANTIQUEIRA RANGE, SOUTHEASTERN BRAZIL

LAVRAS - MG
2015

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Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Pós-Graduação em Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Doutor.

Orientador
Dr. Nilton Curi

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(HIDROPEDOLOGIA NA SERRA DA MANTIQUEIRA, SUDESTE DO BRASIL)

Tese apresentada à Universidade Federal de Lavras, como parte das exigências do Programa de Ciência do Solo, área de concentração em Recursos Ambientais e Uso da Terra, para a obtenção do título de Doutor.

Aprovada em 29 de julho de 2015.

Dr. Carlos Rogério de Mello	UFLA
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RESUMO GERAL

PINTO, Leandro Campos. **Hydropedology at the Mantiqueira Range, Southeastern Brazil.** 2015. 165 p. Tese (Doutorado em Ciência do Solo) – Universidade Federal de Lavras, MG.[*]

Um dos grandes desafios que a sociedade enfrentará nos próximos anos será o de utilizar os recursos naturais de forma sustentável. No Brasil, a Mata Atlântica está desaparecendo a um ritmo elevado. Atualmente, existem apenas 7% da área original distribuída em pequenos fragmentos, principalmente em áreas de difícil acesso, como a Serra da Mantiqueira. Nessas áreas, os solos são predominantemente Cambissolos, que se constituem em unidades pedológicas muito frágeis fisicamente, devido à sua estrutura pouco desenvolvida. As alterações no uso do solo combinadas com a pequena profundidade dos Cambissolos, levam a impactos importantes na hidrologia desta região. Por isso, os estudos que abordam o comportamento de vazões nestas paisagens são urgentemente necessários para a compreensão do processo de recarga das águas subterrâneas. Portanto, este estudo teve como objetivos: caracterizar um Cambissolo altimontano sob clima subtropical de altitude no Sudeste do Brasil, através de análises físicas, químicas e micromorfológicas do solo, em floresta nativa e pastagem; investigar o papel dos Cambissolos ligado às mudanças de uso do solo no comportamento de vazões da região da Serra da Mantiqueira para melhor compreender os mecanismos de fluxo de água na zona saturada; e avaliar a aplicação de reconhecimento de padrões em ferramentas de classificação da paisagem, combinadas com técnicas de mapeamento digital de solos para o mapeamento da transmissividade de água no solo na Serra da Mantiqueira, Sudeste do Brasil. As análises micromorfológicas sugeriram um estágio intermediário de intemperismo mineral e desenvolvimento do solo, o que está de acordo com as propriedades esperadas em Cambissolos. O balanço hídrico durante os anos de 2009/2011 mostrou que o fluxo armazenado na zona saturada em Cambissolos sob floresta, ocorre rapidamente, aumentando o seu potencial de armazenamento, e caracterizando um processo de recarga de água. As áreas com florestas nativas desempenham um papel fundamental nos processos de distribuição de água no perfil do solo em bacias hidrográficas de cabeceira do Sudeste do Brasil. Isso reforça a importância de adequadas práticas de conservação e uso do solo neste tipo de ambiente no Brasil.

Palavras-chave: formação do solo; recarga de água; Floresta Atlântica, hidropedologia.

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[*] Orientadores: Nilton Curi – UFLA e Carlos Rogério de Mello – UFLA.

GENERAL ABSTRACT

PINTO, Leandro Campos. **Hydropedology at the Mantiqueira Range, Southeastern Brazil.** 2015. 165 p. Dissertation (Doctorate in Soil Science) – Federal University of Lavras, Lavras, MG.[*]

One of the greatest challenges facing society in the coming years will be to use natural resources in a sustainable manner. In the Southeast of Brazil, the Atlantic Forest is disappearing at an elevated rate. Currently only 7% of the original area exists as mostly fragmented remnants distributed over areas difficult to access, such as Mantiqueira Range. In these areas, the predominant soils are Inceptisols, which constitute very fragile soil systems. Land-use changing combined with shallow Inceptisols lead to important impacts on hydrology. Therefore, studies that address streamflow behavior in these landscapes are urgently needed for understanding the groundwater recharge process. In headwater watersheds, knowledge about spatial distribution of soil-water transmissivity can be important to support the sustainable use and conservation of the environmental resources. This study aimed: to characterize a mountainous Inceptisol under a highland tropical climate in Southeastern Brazil, taking into consideration the soil physical, chemical and micromorphological analyses, under native forest and extensive pasture; to investigate the role of shallow Inceptisols linked to the land use changes in the streamflow behavior at Mantiqueira Range region, and to understand the mechanisms of water flow into the saturated zone; and to evaluate the application of pattern recognition on landscape classification tools combined with digital soil mapping techniques for soil-water transmissivity mapping in a watershed located at the most important Brazilian headwaters, in Southeastern Brazil. Micromorphological analysis suggested an intermediate stage of mineral weathering and soil development, which is in accordance with properties expected to be found in Inceptisols. Water balance for two years (2009-2011) showed that the flow stored in the saturated zone in Inceptisols under forest occurs rapidly, increasing its potential for storage, characterized by the process of refilling water. Areas with native forest play a fundamental role in water distribution processes in the soil profile in mountainous catchments in Southeastern Brazil. These results strengthen the importance of soil conservation practices and adequate land-use to maintain the water yield in this environment in Brazil.

Keywords: soil formation; water recharge; Atlantic Forest; hydropedology.

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[*] Advisors: Nilton Curi – UFLA and Carlos Rogério de Mello – UFLA.

SUMMARY

FIRST PART

1 GENERAL INTRODUCTION

One of the greatest challenges facing society in the coming years will be to use natural resources in a sustainable manner. In a global scenario of increasing population, the United Nations for Food and Agriculture Organization (FAO-UN) forecasts that Brazilian agricultural output will grow up faster than any other country in the next decade, and will increase up to 40% by 2019 (TOLLEFSON, 2010). Thus, the understanding of how soil attribute's behavior in a watershed is very important for supporting sustainable uses and for conservation of the environmental resources.

Southeastern Brazil is suffering the worst drought in decades, which is threatening water supply, electric energy generation, agriculture productivity and potentially the economic growth of the country. The expression of the drought was particularly evident in the summer of 2013/2014 and early 2015 (rainy period in this region), where the precipitation was much lower than average (INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS / CENTRO DE PREVISÃO DE TEMPO E ESTUDOS CLIMÁTICOS - INPE/CPTEC, 2014; COELHO et al., 2015).

Nevertheless, there were several possible reasons for this drought as the climate system is interconnected with the physical, chemical and biological features of the planet. We can highlight the global warming, to the Amazon Forest deforestation and there is a closer relationship with Atlantic Forest deforestation, which has been responsible for reduced groundwater recharge in the region in the above mentioned period.

In the Southeastern Brazil, Atlantic Forest is disappearing at an elevated rate. Originally, this Brazilian ecosystem had over 1.48 million km² (17% of the

Brazilian territory) (RIBEIRO et al., 2009). However, currently, only 7% of the original area exists as mostly fragmented remnants distributed over areas difficult to access, such as steep hills and mountainous areas (VIEIRA et al., 2008). Currently researches have demonstrated the importance of maintaining or restoring forest cover in the Atlantic Forest above 30% threshold to maintain the ecological balance (BANKS-LEITE et al., 2014).

In this sense, a better understanding of how water flows into the aquifers and streamflows is necessary so that local conservation and management strategies can take place.

2 HYDROPEDOLOGY

2.1 Fundamental concepts

2.1.1 Interviewing soil and hydrology

Nowadays, the concern with natural resources has been more and more necessary, as soil and water are fundamental elements to understand the balance between the need for agricultural, livestock production and environmental sustainability. In this context, the relationship between two branches of science (pedology and hydrology) has been debated and analyzed in recent years, contributing to creation of a multidisciplinary science, which seeks to integrate the respective fields of the knowledge (MELLO; CURI, 2012). Hydrologic studies related to water movement in the soil profile are fundamental for water budget analyses, which should be supported by pedologic and geomorphologic concepts. This science has been commonly called “Hydropedology”.

Hydropedology is the interweaving of Soil Science and Hydrology, promoting the interface between pedosphere and hydrosphere with emphasis on soils and associated landscapes (LIN, 2012). This new way of looking at these two branches of knowledge consists of a science whose approach is typically multidisciplinary and its application is quite wide, providing significant contributions for better understanding of soil-water-landscape interactions (MELLO; CURI, 2012).

According to Kutilek and Nielsen (2007), hydropedology provides the bridge between the disciplines of pedology, including soil micromorphology and vadose zone, and hydrology besides other disciplines that deal with land, air and water interfaces. A natural link between pedology, soil physics, and hydrology (LIN, 2003), creates an unique tool to address problems that affect the environment (VEPRASKAS; HEITMAN; AUSTIN, 2009), mainly in the pedosphere and hydrosphere interface (LIN et al. 2006; LIN, 2010; 2011).

For Pedology, Hydrology can be fundamental to understand the soil formation processes in different landscapes (MELLO; CURI, 2012). The authors stressed the importance of the hydropedology for the pedogenesis, and the insertion of the Pedology in the theories of Hydrology. This interweaving between soil and water will allow the development of more realistic physical based hydrological models, with less parameterization, which is now one of the most important challenges for the hydrologists.

According to Lin (2003), despite of different research methods involved with pedology, soil physics and hydrology, the synergism between these disciplines has mutually benefited each other's work. This type of research is well positioned to solve contemporary problems that deal with land use and water issues in environmental sets.

Lin et al. (2006) presented a vision that advocates hydropedology as an advantageous integration of soil science and hydrology to study the intimate relationship between soil, landscape and hydrology.

The best way to show the usefulness of hydropedology is to demonstrate its effectiveness in addressing issues of interest of the public in general. It is understood that the current limitations in watersheds modeling like groundwater recharge process and soil loss in agricultural landscapes are of great concern to farmers and environmentalists.

Lin (2003) mentioned that although there is a long history of linking the disciplines of soil science and hydrology, there is a renewed emphasis on this partnership because of their relevance to many important questions, such as: water quality, quality of soil, landscape processes, watershed management, nutrient cycling, ecosystem health, climate change, land use planning and precision farming.

Bryant et al. (2006) suggested that hydrologists must work with modellings in a framework that combines hydrology and soil science to make changes that overcome current deficiencies in watershed models aiming to improve hydrology modeling in watersheds for partitioning precipitation into infiltration and surface runoff. Therefore, this field of investigation has great importance for the understanding of soil hydrological behavior.

Lin et al. (2015) reported that decisions regarding the management of soil and water should incorporate a perception of soils and hydrology as a complex system. The authors warn that these decisions need to be truly science-based, aiming at a new level of understanding of the complexity of soil hydrology and ecosystems. Allen et al. (2009) introduced the hierarchy theory to examine complexity in hydropedological investigations and concluded that this theory favors a more systematic and robust integration between hydrology and soil science.

Pachepsky et al. (2008) cited that this discipline emerges as a logical consequence of the progress in science and the timely response to the society needs. Lin et al. (2008) analyzed the contributions from hydropedology to the understanding and modelling of surface/subsurface runoff processes, integrating these phenomena in different scales from micro-to macro-scales. In other words, observations made by pedologists can significantly improve the quality of the parameter measurements by hydrologists, and thus, to be used in a modelling process (Bouma, 2006). A key central question facing hydropedologists is how to determine appropriate measurements and to associate them to modeling parameters for a spatio-temporal scale of interest (Lin et al., 2006).

According to Bouma (2006), to address global environmental in international panels issues, hydrologists and soil scientists have a very important role in the formulation of environmental policies. Yet, the combination between pedology and hydrology expertise can be particularly attractive when presenting soil information to panels dealing with environmental policies, showing results of different types of knowledge, applied at different spatial levels.

Hydropedology requires innovative techniques for improving quantification of soil's architecture at different scales since this science calls for a new era of soil research that is based on soil architecture and structure, and requires that the prediction of flow pathways, patterns, and residence time be done in a more realistic way (LIN, 2010).

Synergies of integrating pedologic and hydrologic knowledge for enhancing the understanding of soil moisture and hydrologic dynamics in watersheds can be shown by hydropedology investigations about fundamental processes of landscape water fluxes at multiple scales (LIN, 2006). Lin and Zhou (2008), using soil hydrologic monitoring in a small catchment in the eastern United States, demonstrated that a combined consideration of soil types and landscape features is important to ensure proper use of the soil data for hydrological applications.

In studies related to groundwater recharge it is essential to consider hydropedology features of the region, because the soil is an essential element for the functioning of the water cycle, storing and transmitting water to the saturated zone and then to the drainage channel systems.

Hydropedology can also be linked to other disciplines, like hydrogeology. In this sense, Lin (2003) cited that the interaction between hydrology and geology can provide a systematic approach to the study of the earth's surface and subsurface environments such as the analysis of integrated studies of the critical zone, which is one of the most attractive knowledge areas for research in the 21st century (KUTILEK; NIELSEN, 2007). Lin et al. (2006) presented a vision for developing and promoting hydropedology as a new interdisciplinary science that embraces multiscale basic and applied researches of interacting pedology and hydrology processes and their properties in the vadose zone.

Among several key topics suggested by Lin; Drohan; Green (2015) for advancing in hydropedology in the next years, can be highlighted the need for an advance in application of technologies for better understanding soil structure and derived preferential flow. The use of X-Ray computed tomography, new tracers for preferential flow, and new types of simulation models that capture realistic flow paths and standards, seem to be the major challenges and frontiers in hydropedology, mainly in the tropical region.

2.1.2 Critical zone

The Critical Zone (CZ) consists in a heterogeneous and complex layer on the planet Earth, being a holistic framework layer for integrated studies of water, soil, rock, air, and biotic resources. Originally, CZ covers the region from the top of vegetation (canopy) to bottom of the aquifer, with a highly variable thickness and a yet-to-be clearly defined lower boundary of active water cycle (LIN, 2010).

The vadose zone is a substantial part of the critical zone (PACHEPSKY et al., 2008), wherein the latter occurs the main processes associated to the hydrological cycle, the vegetable covering and their relationships with the atmosphere, pedosphere, hydrosphere and the lithosphere (LIN, 2010; MELLO; CURI, 2012).

Since the retention and water flow in the vadose zone, directly or indirectly affects all processes of this zone, an understanding of the hydrology of the critical zone is required (PACHEPSKY et al., 2008).

In recent years, studies on the vadose zone have been considerably increased, especially in the plant's root zone, focused on the water flow, on the fate and transport of nutrients and on agricultural contaminants in the soil (PACHEPSKY et al., 2008).

Li et al. (2013) investigated how soil water dynamics together with plants may generate subsurface structures, showing complex interactions among vegetation, soil structure, and soil water dynamics revealing important interrelationships between hydropedology and ecohydrology and how soil moisture and plant growth influence each other.

According to Lin (2010), hydropedology is an important contributor to critical zone study, because it is a science of the behavior and distribution of soil-water interactions in contact with mineral and biological materials in the critical zone.

2.1.3 Land use influence

The hydrologic effects of forest use and reforestation of degraded lands in the humid tropics have implications for local and regional ecological services, but such issues have been relatively less studied when compared to the impacts of forest conversion to pasture and crop sites.

Despite approximately 500 years of intense land use changes in the Atlantic Forest, the influence of land use changes on hydrological processes has not been properly investigated (SALEMI et al., 2013). The severe drought that have affected Southeastern Brazil in the 2013/ 2014 summer and early 2015 can be linked to some global climate interactions, although, Arruat et al. (2012) and Nobre (2014) have done some connections with deforestation of Amazonian forest. So, a closer relationship with deforestation of Atlantic Forest has been neglected. The role of this native forest ecosystem on the hydrology of headwater basins has been reported based on a significant number of field investigations (SALEMI et al., 2013; ÁVILA, 2011; MENEZES et al., 2009). There is a consensus that deforestation of the native forests has interfered with the maintenance of water supply from watersheds, decreasing its ability for water recharge and natural regularization of flows. In this context, deforestation of the Mantiqueira Range region has caused a fast reduction of the natural regulation of streamflow, leading to scarce water and more frequent and acute drought (VIOLA et al., 2015; MENEZES et al., 2009).

Whereas groundwater recharge in the Mantiqueira Range region is sensitive to use and management of soils (MENEZES et al., 2009; ALVARENGA et al., 2012; VIOLA et al., 2014), the areas where the predominant land use is native forest have proved to present better conditions for groundwater recharge, and thus, for mitigating the effects from possible global warming impacts. In addition to this, understanding soil formation processes across different landscapes is needed to predict how soil properties will respond to land use change.

According to Benites et al. (2007), soils under native forest in Mantiqueira Range are relatively stable, but after land use changes to pastures, they become rapidly degraded, chiefly by erosion, loss of organic matter and natural fertility depletion.

More importantly, the influence of land use changes on hydrological processes must be investigated within this region since major land use changes have been observed. It is necessary to obtain a complete understanding of the hydrologic function of the landscape related to the change in land use within areas previously occupied by forests that are now being utilized as low productivity pastures (SALEMI et al., 2013).

Zimmermann et al. (2006) investigated the effects of land use in areas of the Amazon Basin and reported that the more intensive the land use, the more pronounced the decrease in saturated hydraulic conductivity values. Thus, the surface runoff component is more frequent under pasture land use when compared to native conditions or successional forests. These results demonstrate that pasture in these regions strongly affects the saturated hydraulic conductivity values.

Salemi et al. (2013) studying three small catchments covered by pristine original montain cloud forest, pasture, and eucalyptus, found a significant higher saturated hydraulic conductivity values at 0.15 m depth in soils under forest when compared to eucalyptus and pasture.

Price et al. (2010) studying soil hydraulic properties across land uses in the southern Blue Ridge Mountains of North Carolina, USA, found saturated conductivity hydraulic values inside forests approximately seven times greater than in pastured. These authors stressed that the differences in soil hydraulic properties between forested and nonforested soils are due to a combination of land management and differences in macropore-forming biotic activity. In this sense, the presence of native forests in an advanced stage of development provides better conditions for the genesis of gravitational pores with high drainable porosity and soil saturated hydraulic conductivity, with formation of preferential flows throughout the soil profile (ACREMAN et al., 2012; BONELL et al., 2010; HÜMANN et al., 2011; ROA-GARCIA et al., 2011).

Pinto et al. (2013) and Pinto; Mello; Ávila (2013), evaluating the water quality of the Lavrinha Creek Watershed, in the Mantiqueira Range region, verified that the water quality indexes of the catchment with forest presented better results in comparison with the catchment with pasture, proving the importance of the regional native forests for the water quality maintenance. In other words, the forest environment has better water quality results than the pasture environment, due to the greater protection that the first provides to watercourses.

Viola et al. (2013) simulated the hydrological impacts in four watersheds with similar climate and soil characteristics in the Upper Grande River Basin, and concluded that differences in runoff components within these watersheds are mainly linked to land use differences and that the greatest contributions of surface runoff were found in watersheds with areas occupied by agriculture and pasture. These types of land use produce more surface runoff than forested areas because soils cultivated with crops and pastures tend to suffer more physical degradation, thus affecting their infiltration capacity.

Price et al. (2010), in hydrological studies carried out in mountainous catchments, verified that the conversion of native vegetation to agriculture reduced soil infiltration and soil-water storage capabilities, resulting in increased surface runoff and reduced subsurface storage. The results of Germer et al. (2010), in studies involving land use change on near-surface hydrological processes in the Amazon Basin, show that conversion of undisturbed forest to pasture not only increased frequency and volume of stormflow, but also the contributing area and the manner in which the water moves into and through soil towards the drainage channels. Pietola; Horn; Yli-Halla (2005) found a significant difference in water infiltration between trampled and non-trampled soils by cattle, even though the grazing intensity had been low.

The spatial identification of promising areas in the context of water recharge allows for better land use planning in order to maintain a sustainable water supply (VIOLA et al., 2015). Tsui; Chen; Hsieh (2004) researching the relationships between soil properties and slope positions in a lowland rain forest of Southern Taiwan, found an increase of organic carbon and lower rate of decomposition in the summit forest. Other authors found similar results and cited that these results are due to the forest, which is in a system without human activity and provides great amount of organic matter to the environment (BEUTLER et al., 2002; RAWLS et al., 2003).

Don; Schumacher; Freibauer (2011) found an average increase of 14% in soil bulk density comparing the original vegetation and the agriculture field, reviewing several studies on land conversion in the tropics. The difference of bulk density between forest and pasture might be ascribed to the compaction of the topsoil due to animal trampling on the pastures (CELIK, 2005), and the lack of soil conservation.

2.2 Tools for studying Hydropedology

2.2.1 Micromorphology

Soil micromorphological analysis corresponds to a morphological observation technique in micrometer scale, which requires pedological samples of undisturbed material properly collected, previously impregnated with resins, and finally cut and mounted onto glass slides similarly to petrographic thin sections (CASTRO et al., 2003). According to Castro et al. (2003), this technique includes a detailed study of the components of soil horizons and their relationships, their degree of preservation related to the gains or losses, contributing to important deductions about soil processes involved, either natural or induced by uses and, or, managements. Therefore, the micromorphology is important for research on management, classification and genesis of soils (STOOPS, 2003), and monitoring of various agricultural practices (SOUZA et al., 2006). The use of this technique can reach adequate results in getting evidence on changes on soil physical properties (CASTRO et al., 2003), allowing direct assessment of soil aggregation under field conditions (ZINN, 2005).

Silva et al. (2012) found that the soil micromorphological analysis, besides confirming the soil field morphology, subsidized important information in terms of the unequivocal identification of cases which had not been identified in the field.

The micromorphology has been used to characterize the soil porous system with successful. According to Cooper et al. (2013), the use of micromorphology technique in the characterization of soil porous space can provide detailed information on the conditions of soil structure, especially when the agronomic and management conditions of the studied area are known.

The theory on soil water has advanced enough to include results of micromorphological research of soil porous systems in theoretical studies and in physical models of soil hydraulic functions (KUTILEK; NIELSEN, 2007), applied to specify flow domains in soils and to select numerical models for simulation of water flow and herbicide transport (KODESOVA, 2009).

Soil micromorphology technique in the characterization of preferential flow of water in the soil profile has become attractive because the pores can be measured very accurately in terms of size, shape and number (BOUMA, 1981). These physically based parameters of soil hydraulic functions could be then related to topological characteristics of the soil porous system or to realistic models of the soil porous system derived from the direct micromorphologic observations (KUTILEK; NIELSEN, 2007). Other studies have demonstrated the impact of soil organisms and different vegetation cover on soil pore structure and hydraulic properties of surface soils (KODESOVA et al., 2006; 2007).

Pires et al. (2008) used image analysis to characterize structure modifications of soil samples submitted to wetting and drying cycles. The authors verified that this type of information is very important for the evaluation of soil-water retention curves and other soil hydrologic properties.

The porosity usually is determined in relation to the matric potential. Therefore, using the soil image analysis, it is possible to see the pore shape and connectivity, providing detailed information on the soil structure (COOPER et al., 2013) and helping to understand the movement of water in the soil profile.

Pagliai and Kutilek (2008), in a characterization of soil porosity by micromorphological approach, demonstrated the importance of pore characterization to understand water movement in soils. Therefore, the micromorphology analysis of the structure and the associated pores would add important value to identification of preferential flows, especially in headwater soil landscapes occupied by native forests (MELLO; CURI, 2012).

The study on the pore scale is closely related to micromorphologic features of soils (KUTILEK; NIELSEN, 2007). The authors showed some results of research about soil structure and micromorphological characteristics and processes, demonstrating its potential for application in hydropedological research.

Micromorphology brings a better understanding of pore space configuration (KUTILEK; NIELSEN, 2007), and the peculiar behavior of hardsetting horizons (LIMA et al., 2006). In other words, the soil micromorphology acts as an integrating tool for all soil disciplines involved (BLUM, 2008).

Boixadera; Antúnez; Poch (2008) analyzed the **s**oil evolution along a toposequence on glacial materials in Spain and concluded that the soil formation processes have been mainly identified through micromorphological techniques that allowed the scaling down from soil-landscape relationships to horizon morphology.

According to Castro et al. (2003), the soil micromorphology is an observation technique that, by itself, does not answer all the questions raised in pedological research and, therefore, may not be exempted of analytical results obtained by other techniques.

2.3 Digital Soil Mapping tools

2.3.1 Fuzzy Logic

With the advances of computational sciences, soil scientists have increased access to Digital Elevation Models (DEM), available at different resolutions, which can aid in relating soils differentiation based on relief, soil expert knowledge, and mapping techniques, such as fuzzy logic (MENEZES et al., 2013; SILVA et al., 2014).

Zhu et al. (1996) and Zhu et al. (1997) presented a methodology combining fuzzy logic with geographic information and expert system development techniques in order to infer and represent soil information on the spatial resolution.

This method is based on the premise that the knowledge of a soil scientist and an understanding of soil-landscape relationships act as a based model to predict classes and soil properties (ASHTEKAR; OWENS, 2013; SILVA et al., 2014).

Techniques for digital soil mapping based on the use of fuzzy logic allow a faster production of soil survey and continuously adjust the spatial distribution of soil properties into discrete categories according to the complexity of the variability of them, increasing the accuracy of information in space (MENEZES et al., 2013).

Soil attributes are likely to be predicted by means of fuzzy logic, similarity vectors (ZHU et al., 1997) and a software package for knowledge-based raster soil mapping (SHI et al., 2009).

According to Menezes et al. (2013), in the digital soil mapping the soils expert knowledge can be incorporated into spatial prediction, where the qualitative soil-landscape model is converted into quantitative predictions using relationships between soils and, more frequently, terrain attributes, such as altitude, slope, topographic wetness index, plan curvature and profile curvature.

Fuzzy logic has shown adequate performance for soil mapping and their attributes prediction (ZHU; BAND, 1994; ZHU et al., 1997; 2001; ZHU; LIN, 2010) and has been successfully applied in the prediction of hydropedological attributes, like soil-water transmissivity and soil hydraulic conductivity (ZHU et al., 1997).

Its application in a hydropedological context can be a very promising tool, helping the understanding of how the water interacts with landscape features. In this context, Holleran; Levi; Rasmussen (2015), using digital soil mapping techniques to quantify and predict the spatial distribution of soil properties, verified that these techniques provide a framework for interpreting catchment-scale variation in critical zone process and evolution.

Recently, several studies concerning distribution of soil properties have been published applying environmental variables like terrain attributes (ASHTEKAR; OWENS, 2013; GREVE et al., 2012; MENEZES et al., 2014; SILVA et al., 2014; SILVA et al., 2015).

Menezes et al. (2014) presented a solum depth spatial prediction in a watershed at Mantiqueira Range, Brazil, from knowledge-based digital soil mapping. The authors concluded that the use of terrain attributes derived from digital elevation models in predicting soil properties using fuzzy logic may provide adequate results for study areas with various soil types and difficult access.

In this sense, the association between fuzzy logic and hydropedological attributes can provide a significant contribution for better understanding of the soil-water interaction in a specific landscape.

2.3.2 Geomorphons

Jasiewicz and Stepinski (2013) performed a landform classification, called “Geomorphons”. Geomorphons is a mapping tool that identifies landforms within a landscape through DEM analysis. This tool has small computational effort and utilizes the concept of Local Ternary Patterns (LTP) (LIAO, 2010). A local pattern is determined using a neighborhood with size and shape that self-adapts to the local topography.

From a typical terrestrial landscape, the most frequent and commonly landform elements used in many geomorphology classifications according to Jasiewicz and Stepinski (2013) are: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit.

Toma et al. (2015) used the “Geomorphons” in order to better understand the relationships between this landform classification and soil organic matter content in soils under *Eucalyptus* plantations, at South Brazil. The authors found a relationship between soil organic carbon at the 0-5 cm depth and the landscape form (Geomorphons) and slope gradient using a Geographic Information System (GIS).

Ashtekar et al. (2014), mapping soils in the region of the Llanos Orientales, South America, used the Geomorphons tools (JASIEWICZ; STEPINSKI, 2013). The authors grouped the soils into 5 geomorphic units of the Geomorphons, and verified that these geomorphic units were able to capture the variability of terrain and driver of soil differentiation better than the original polygon mapping units from the detained soil map currently available for the Llanos.

It is noticed that the Geomorphons is a promising tool for hydropedology, providing additional details on each of the soil types identified in the catchment, either as the composition of hydrological models, assisting in understanding the behavior of water in the soil profile in the landscape.

3 THESIS STRUCTURE

This thesis, based on the concept of interdisciplinarity of Hydropedology, suggests a renewed perspective and a more integrated approach to study the soil-water interactions across spatial and temporal scales (LIN, 2003) in the Mantiqueira Range region, demonstrating the interaction between Pedology and Hydrology in the landscape, integrating, in turn, the different scales of observation (from microscopic to macroscopic level) of both sciences (MELLO; CURI, 2012) (Figure 1).

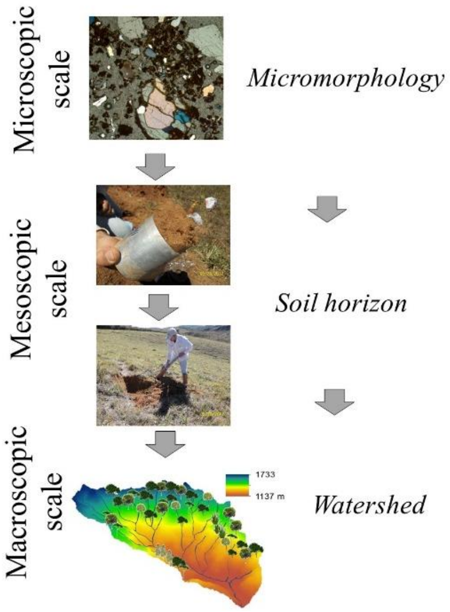

Figure 1. Fundamental characteristic of Hydropedology: connection between the micro-, meso- and macro-scales. Adapted from Lin (2003), and Mello and Curi (2012).

This study was conducted in the Mantiqueira Range region, Bocaina de Minas County, Minas Gerais State, Southeastern Brazil.

The first chapter of the thesis brings a characterization of mountainous Inceptisols (Cambisols) under Highland Tropical Climate (Cwb Köppen classification), using soil physical, chemical and micromorphological analyses, under native forest and extensive pasture conditions.

The objective of the second chapter was to investigate the role of shallow Inceptisols linked to the land use changes on the streamflow behavior of the Mantiqueira Range region and to understand the mechanisms of water flow into the saturated zone. Finally, in the third chapter, we evaluated the application of pattern recognition using landscape classification tools combined with digital soil mapping techniques for mapping soil-water transmissivity in a watershed located at one of the most important headwaters in Southeastern Brazil.

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SECOND PART – PAPERS

PAPER 1

MICROMORPHOLOGY AND PEDOGENESIS OF MOUNTAINOUS INCEPTISOLS IN THE MANTIQUEIRA RANGE (MG)

Micromorfologia e pedogênese de Cambissolos altimontanos na Serra da Mantiqueira (MG)

Normas da Revista Ciência e Agrotecnologia (versão aceita)

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ABSTRACT

Understanding soil formation processes across different landscapes is needed to predict how soil properties will respond to land use change. This study aimed to characterize mountainous Inceptisols (Cambisols) under high altitude subtropical climate in southeastern Brazil, by soil physical, chemical and micromorphological analyses, under native forest and pasture. The soil under pasture had a greater bulk density than under forest, resulting in a severe reduction of macroporosity. At two depths, coarse quartz grains are angular, suggesting absence of transportational processes, thus confirming an autochthonous pedogenesis from the underlying gneissic rock. Most feldspars were weathered beyond recognition, but mineral alteration was commonly seen across cleavage plans and edges of micas. The micromorphological results suggest an intermediate stage of mineral weathering and soil development, which is in accordance with properties expected to be found in Inceptisols.

Index terms: soil formation, soil microstructure, land use change, forest soils.

RESUMO

Há a necessidade de se compreender os processos de formação do solo em diferentes paisagens para prever como as propriedades do solo irão responder às mudanças no uso do solo. Este estudo teve como objetivo caracterizar Cambissolos em uma região montanhosa sob clima subtropical de altitude no Sudeste do Brasil, através de análises físicas, químicas e micromorfológicas do solo, sob mata nativa e pastagem. O solo sob pastagem apresentou maior densidade do solo do que sob mata, expressa pela intensa redução de macroporosidade na primeira condição. Em ambas profundidades, os grãos de quartzo grosseiros são angulares, sugerindo ausência de quaisquer processos de transporte, confirmando assim uma pedogênese autóctone a partir da rocha gnáissica subjacente. A maioria dos feldspatos se encontra intemperizada e não mais identificável, mas a alteração mineral é comumente vista ao longo de planos de clivagem e bordas de micas. Os resultados micromorfólogicos sugerem um estágio intermediário de intemperismo mineral e desenvolvimento do solo, o que está de acordo com as propriedades esperadas em Cambissolos.

Termos para indexação: formação do solo, microestrutura do solo, mudança no uso da terra, solos florestais.

INTRODUCTION

Over the years, soil scientists have delineated concepts and models of soil formation to improve our knowledge of pedogenesis (Stockmann, Minasny and McBratney, 2014). Soil description, characterization and data interpretation must be undertaken within a perspective of its inherent association to local geology and geomorphology, helping to understand the distribution of different soils and the variability of their properties across the landscapes (Barbosa, Lacerda and Bilich, 2009). In subtropical humid regions, the high silt/clay ratio of the Inceptisols, coupled with small solum thickness (A + B horizons), and low natural soil fertility in mountainous relief make this an unstable and fragile system (Resende et al., 1988).

Mountainous soils in high altitude subtropical regions constitute unique and fragile environments, with highly endemic vegetation (altimountainous cloud forests) that are important refuges for animal and plant life (Simas et al., 2005). In Southeastern Brazil, the Mantiqueira

Range is a 500 km long Archean rocky mass that borders three States and often reaches altitudes between 1,500 and 2,900 m a.s.l. This is one of the most important headwater regions in SE Brazil, although its steep slopes, abundant rainfall and shallow to moderately deep soils (Silva et al., 2014) causes a high potential risk of erosion and mass wasting. The distribution of soils in the Mantiqueira Range is mainly influenced by lithology (Dias et al., 2003) and topography. The steep slopes help to promote accelerated erosion, and a rather resistant to weathering gneissic bedrock are both factors leading to the presence of Inceptisols (Cambisols) (Santos et al., 2010). According to Benites et al. (2003), under native forests these soils are relatively stable, but after land use changes to pastures, they become rapidly degraded, chiefly by erosion, loss of organic matter and natural fertility depletion.

According to Buol et al. (2011), relatively few studies have focused on Inceptisols, although this presents an opportunity to study the weathering of minerals and better understanding the early stages of many pedogenic processes. Thus, the aim of this study was to employ soil micromorphology to characterize Inceptisols in the Mantiqueira Range

(MG), improving the understanding of how soil genesis proceeds under such conditions.

MATERIAL AND METHODS

Site description

The Lavrinha Creek watershed (Figure 1) is an experimental area in which many hydrologic, climatic and soil investigations have been carried out since 2004 (Mello et al., 2011). It is located in the southeastern part of the State of Minas Gerais, Brazil, within the Mantiqueira Range physiographical region. A digital elevation model based on a 1:50,000 chart and GPS data was built in 30 vs. 30 m pixels and shown in Figure 1. The watershed has an area of 676 ha, with elevations between 1,137 and 1,733 m a.s.l.

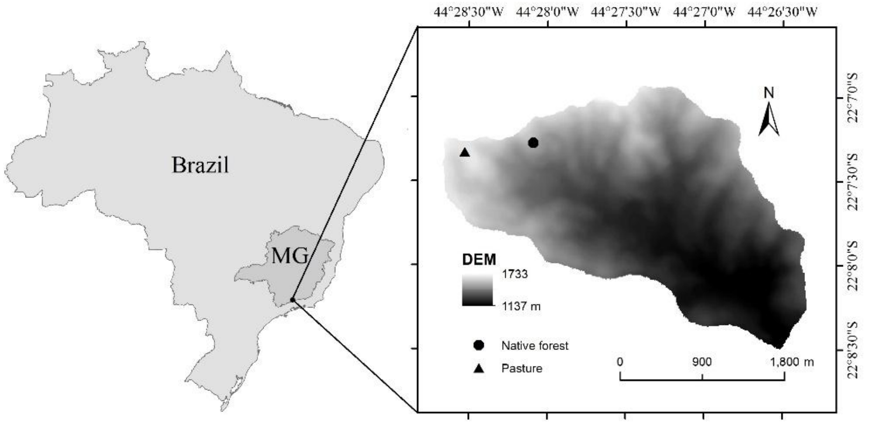

Figure 1. The study watershed in Southeastern Minas Gerais, Brazil.

According to RADAMBRASIL (1983) and Soares et al. (1994), the Andrelândia Group is the most common lithological unit in the southern portion of the Mantiqueira Range. In the studied watershed, the main parent material is Neoproterozoic gneiss (CETEC, 1983; Menezes et al., 2009). Soils are predominantly shallow in the highest parts of the Mantiqueira Range (Benites et al., 2005). Inceptisols (Cambisols) are the main soils, covering 92% of the watershed area, with depths ranging from 0.70 to 1.20 m, including the C horizon (Menezes et al., 2009). These soils are most often used as grazing lands, mainly limited by the relief, high stone content, low natural fertility, and surface crusting, restricting permeability and promoting erosion (Giarola et al., 1997).

According to Mello et al. (2012), local climate is super-humid by the Thornthwaite classification, meaning a highly positive water balance during the whole year. Alternatively, local climate can be classified as Cwb (rainy temperate or altitude subtropical) type by the Köppen classification, with cool winters, with lesser rainfall than the summer. The mean annual precipitation ranged from 1,841 mm to 2,756 mm (2006-2012), with *ca.* 88.3% between September and March. Mean annual temperature is *ca.* 17°C, with average low and high temperatures of 10°C and 23°C, respectively. According to Reboita et al. (2010), most rainfall events are associated with cold fronts throughout the year. However, the South Atlantic Anticyclone, a high-pressure zone that precludes cloud formation, leads to a characteristic dry period during the winter and occasional winter frosts at high elevations.

Approximately 33% of the watershed area is covered by pastures, 5% are under *Eucalyptus grandis* plantations, and the rest is under native forest. The extensive pastures mainly comprise *Brachiaria decumbens* and are currently degraded, with weed invasion and soil surface sealing.

For this study, soil samples were taken only from the two main land uses, namely native forest and pasture. The sampled location under forest presents an average slope of 45% (Ávila et al., 2014), whereas, under pasture (Figure 1) presents very rugged relief class (20-45%) in 67.2% of area and mountainous (45-75%) in 10.9% of area (Oliveira et al., 2014).

Soil analyses

Disturbed and undisturbed soil samples were collected from pit walls at 0-20 and 20-50 cm depths. Particle size distribution was determined by the hydrometer method (Gee and Bauder, 1986), whereas, bulk density was determined by the core method (Blake and Hartge, 1986). Soil organic carbon was determined by the Cantarella, Quaggio and van Raij (2001) method, whereas, soil pH was measured in a 1:2.5 soil/water suspension.

Undisturbed samples for soil micromorphology studies were collected at the same depths (0-20 and 20-50 cm) with a Kubiena box. These samples were air-dried for several weeks, and subsequently dried in an oven at 40°C, 60ºC and 100ºC, to minimize cracking due to rapid drying. The samples were then impregnated with an epoxy resin and de-aerated under vacuum (Castro et al., 2003) for three days to minimize air bubbles, and then heated at 100ºC for 4 hours, and 140ºC for 4 hours for hardening and curing. The hardened resin blocks were cut with a diamond saw, polished on rotating corundum paper and mounted onto glass slides with de-aerated Hillquist® epoxy resin 7A/3B, heated for 1 min. at 105ºC. Finally, the mounted blocks were sectioned and polished to the ideal thickness of 30 µm for micromorphological analysis, as recommended by Murphy (1986), and analyzed with a petrographic microscope.

RESULTS AND DISCUSSION

Soil characterization

The physical and chemical characteristics of the studied soils are presented in Table 1.

Table 1. Soil physical and chemical properties of the studied Inceptisols (Cambisols)

Depth	Clay	Coarse Sand	Fine Sand	Silt	SOM	pH	Bulk density
(cm)	..........................(%)...........................						(kg dm^{-3})
0-20 $_F$	35	28	20	17	9.2	3.3	0.75
20-50 $_F$	29	29	20	22	4	4.2	0.93
0-20 $_P$	32	38	16	14	4.6	4.6	1.03
20-50 $_P$	34	23	18	25	2.9	4.4	1.15

Note: F: soil under native forest; P: soil under pasture; SOM: soil organic matter.

Silt/clay ratios are relatively high, suggesting an intermediate degree of rock weathering, which are associated with the presence of semi-weathered minerals modified by steep reliefs under a humid climate. Soil organic matter (SOM) contents under native forest are high at the 0-20 cm depth, and pH is accordingly very low (Table 1). Such conditions are favored by local high precipitation (~2,000 mm per year) and mildly cool temperatures, even during the summer (Mello et al., 2012). There were losses of ~50% and of ~28% of SOM contents at the 0–20 and 20-50 cm depths, respectively, upon land use change to pasture. In fact, the forest floor accumulates a substantial litter layer approximately 15 cm-thick cm above mineral soil (Santos et al., 2013), protecting against soil erosion and degradation (Alvarenga et al., 2012). The soil under pasture had greater bulk density compared to the soil under forest, which can be ascribed to the compaction (Biggs, Dunne and Muraoka, 2006) and a decrease in SOM. The increase in bulk density at the 0-20 cm depth reported here is much greater than the average increase of 14% reported after clearing of native vegetation in the tropics (Don, Schumacher and Freibauer, 2011). In the pasture area, erosion resulted in some areas with a thin (about 40 cm) solum (A+B horizon) depth (Menezes et al., 2014), particularly on the steepest slopes.

Soil micromorphology

In both soils and depths, coarse quartz grains are angular (Figure 2), suggesting an absence of transportation processes or long-weathering time, thus confirming an autochthonous pedogenesis, i.e. soils were formed in situ and the pedogenesis/erosion rate is limited by the mountainous conditions. Furthermore, the generally elongate shape of quartz grains is in accordance with mid- to high-grade metamorphic rocks, namely orthogneiss.

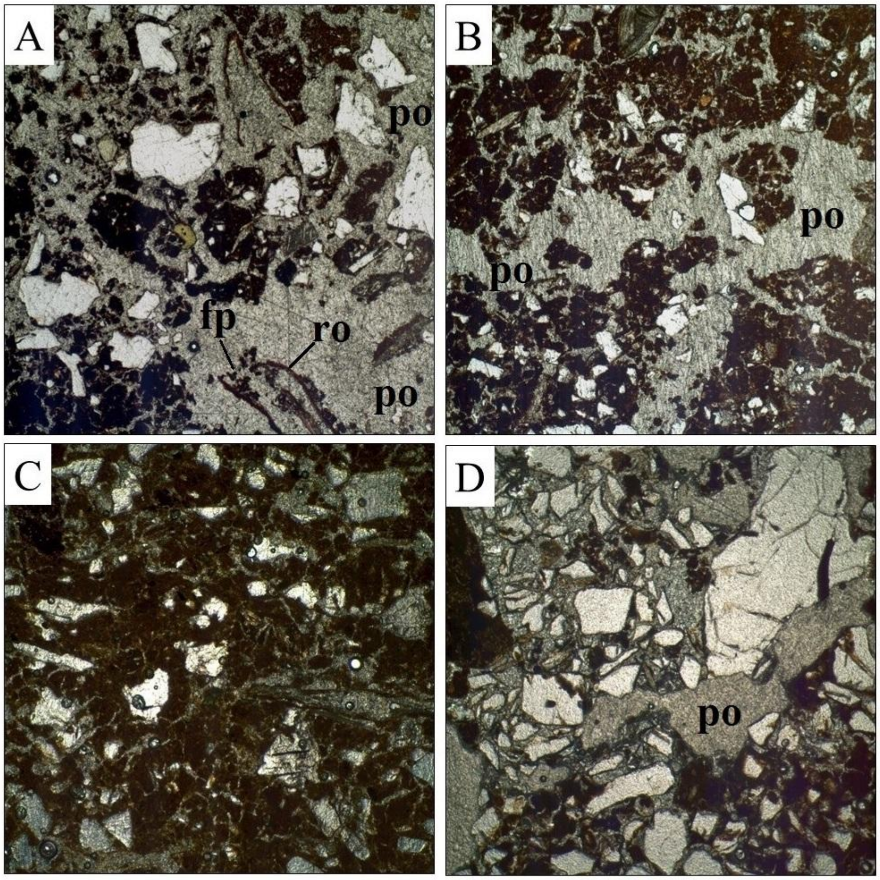

Figure 2. Thin sections of soils under native forest at 0-20 cm (A) and 20-50 cm depths (B), and under pasture at 0-20 cm (C) and 20-50 cm (D) depths. ro: roots; fp: faecal pellets, and po: pores. Frame length is 2.7 mm. All images are under plane-polarized light.

Table 2 presents the porosity and microstructure features of Inceptisol under forest and pasture.

Table 2. Porosity and microstructure features of Inceptisols under native forest and pasture.

Inceptisol (Cambisol)	0-20 cm	20-50 cm
Under native forest	Packing porosity; complex microstructure of moderately developed granular and subangular blocky type	Porosity is much lower; subangular blocky microstructure
Under pasture	Closer-packed and much lower porosity; blocky microstructure	Coarse grain surfaces

Abundant packing porosity is apparent at the 0-20 cm depth of the soil under native forest, amid a complex microstructure of moderately developed granular and subangular blocky type (Figure 2A and Table 2). Accordingly, abundant roots and faecal pellets indicate high biological activity at this depth. At the 20-50 cm depth, porosity is much lower and the subangular blocky microstructure is more developed, separated and partially accommodated in the presence of planar pores, and granules are absent (Figure 2B), in accordance with the morphological description in the field.

In contrast, the soil under pasture (0-20 cm) presents a much closer-packed, blocky microstructure and much lower porosity (Figure 2C), in agreement with the increase in bulk density value (Table 1). At the 20-50 cm depth, the apparent accordance among coarse grain surfaces (Figure 2D), mainly along planes of weakness (Frazier and Graham, 2000), suggests a relatively recent fragmentation of the parent material. Such evidence supports the idea that erosion has made the weathering front closer to the soil surface, i.e., promoting soil rejuvenation.

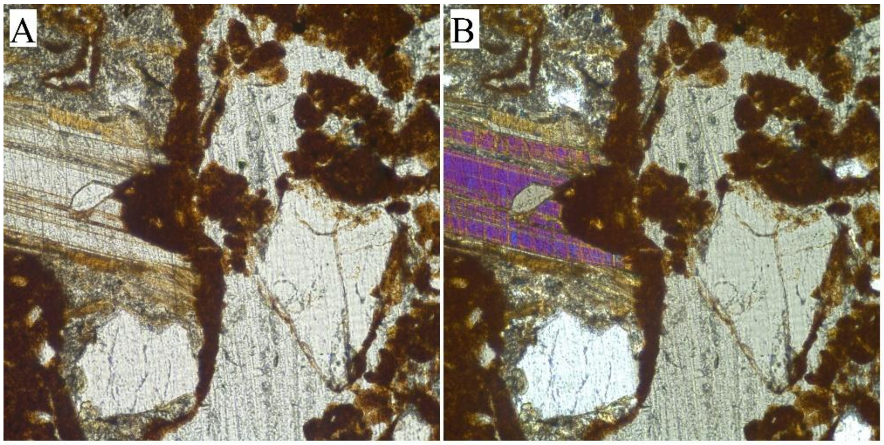

Figure 3. Thin sections of muscovite weathering, 20-50 cm depth. A) under planar polarized light; B) partially crossed polarized light. Frames are 0.5 mm wide. Note exfoliating cleavage of muscovite (lower basal surface) and microfractured feldspar alteromorph with clay masses (upper left).

Intact feldspar grains were not observed, although expected in mountainous soils forming on gneissic rock, as noted by Borrelli et al. (2012) and Le Pera et al. (2001), among others. It is likely that most feldspars were already weathered into grayish, grainy alteromorph masses visible in some thin sections (Figures 3 and 5), in a pattern termed “microfractured” by Borrelli et al. (2012). Such information is reinforced by brownish clay domains, probably neoformed, visible on both images.

However, the mineral alteration most commonly visible is on the basal and edge surfaces of coarse muscovite grains. Under planar polarized light (Figure 3A), the inner parts of muscovite domains appear colorless, with their basal cleavages visible, at times in neatly angular exfoliation. Nevertheless, the outer basal or edge surfaces, in contact with soil or rock fragments, present yellowish to brownish colors, representing the onset of alteration to kaolinite (Stoops, 2003) or hydroxi-interlayered vermiculite (Thompson and Ukrainczyk, 2002), as well as some intrusion by organic matter and/or Fe oxides. The mineralogy of the clay fraction of the B horizon of this soil reveals 62.4% of kaolinite and 32.7% of gibbsite, in agreement with its young-stage development and supports the muscovite → kaolinite and biotite → gibbsite main transformations. Under crossed polars, such alteration is visible by weak, first-order interference (yellowish) colors contrasting strongly with the high-interference (iridescent) colors of unaltered muscovite (Figure 3B). The same occurs for biotite, which however shows yellow to green colors under plane polar light (Figure 4A) and high interference colors under crossed polars (Figure 4B). As expected for Fe-bearing micas, impregnation by Fe-oxides on edge surfaces and in between cleavage plans of biotites (Figure

4) are more prevalent than for muscovites (Figure 3). Similar results were presented by Oliveira et al. (2008).

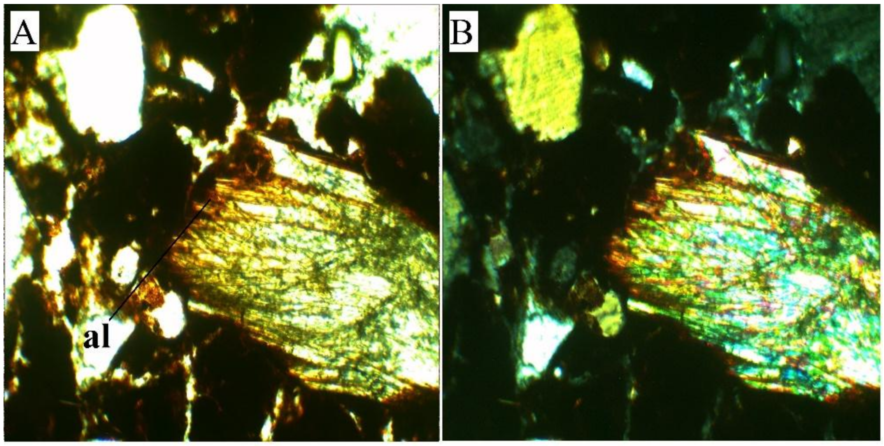

Figure 4. Thin sections of mineral weathering of a biotite domain, 20-50 cm depth. A) under planar polarized light; B) under cross-polarized light. al: alteration in terminal edges and basal cleavage surfaces. Frames are 0.9 mm wide.

Weathered rock fragments are commonly interspersed within the soil matrix as gravels. Figure 5 shows a gneiss fragment, in which the core is composed by welded, elongated quartz grains (Qz) impregnated with an opaque mineral (om, probably a primary Fe oxide), and a brown, unknown mineral. Most interestingly, the surrounding grayish mass exhibits abundant intragranular microcracks typical of heavily altered feldspars, with abundant clay masses (cl), probably neoformed but also deposited as pore coatings. This can be considered *prima facies* evidence of clay formation from the local parent material, i.e., of an autochtonous soil genesis. The clay has not been translocated and layering is not apparent, therefore, warranting classification of Inceptisols.

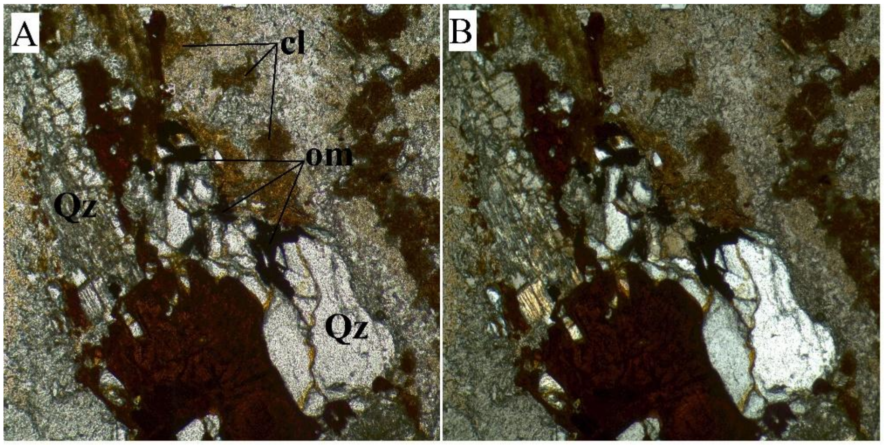

Figure 5. Weathered rock fragment, 20-50 cm depth. A) under planar polarized light; B) under cross-polarized light. The microgranular, gray mass surrounding the core is probably a highly altered feldspar. cl: neoformed clay masses; om: opaque mineral; Qz: quartz. Frames are 0.9 mm wide.

CONCLUSIONS

The micromorphological results reveal an intermediate stage of mineral weathering and soil development, which is in exact accordance with properties expected to be found in mountainous Inceptisols (Cambisols). More specifically, such conclusions were grounded on: a) clay contents within the medium texture class, suggesting an intermediate degree of pedoplasmation; b) advanced stage of weathering of feldspars, the most common rock components; c) considerable presence of micas, not only muscovite but also biotite in the coarse material; d) visible alteration of such micas into secondary phyllosilicates, mostly kaolinite, a mineral typical of subtropical soils in young-stage development. No evidence of translocation was found for the neoformed clays thus supporting the classification of these soils as Inceptisols.

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PAPER 2

Role of Inceptisols in the hydrology of mountainous catchments in Southeastern Brazil

Normas da Revista: Journal of Hydrologic Engineering (versão aceita)

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Abstract: Mantiqueira Range is the most important headwater region in Southeastern Brazil, being responsible for streamflow that feed a significant part of Brazilian hydroelectric energy production. This region is extremely fragile with endemic species like those that compose the Upper Mountain Cloud Forest (UMCF) and the dominant soils are typical

Inceptisols. These forest environments are rapidly disappearing in Brazil. The changing land use combined with shallow Inceptisols lead to important impacts on hydrology. Therefore, studies addressing streamflow behavior in these landscapes are urgently needed for understanding the groundwater recharge process. The objectives of this study were to investigate the role of shallow Inceptisols linked to the land use changes in the streamflow behavior of the Mantiqueira Range region and to understand the mechanisms of water flow into the saturated zone. To validate the study, a comparative analysis was developed for a representative watershed of Mantiqueira Range, whose land use is divided into pasture and Atlantic Forest, known as Lavrinha Creek Watershed (LCW) and a typical UMCF located inside of LCW. The results showed that in general, UMCF has greater potential for water percolation beginning from the surface layer towards the saturated zone. Micromorphological soil images provided useful information about the soil pore system associated with the physical properties of Inceptisols and this background helped to understand the water recharge process and streamflow behavior. In addition, the water balance for two years (2009-2011) in the UMCF showed that the flow stored in the saturated zone

occurs rapidly, increasing its potential for storage, characterized by the process of refilling water in Inceptisols soil profile under forests in this region.

ASCE Subject Headings: Soil water, Groundwater recharge, Hydrology, Evapotranspiration.
Author Keywords: Atlantic Forest; hydropedology; water recharge; micromorphology; streamflow; Mantiqueira Range.

Introduction

One of the greatest challenges facing society in the coming years will be to use natural resources in a sustainable manner. In a global scenario of increasing population, the United Nations Food and Agriculture Organization forecasts that Brazil’s agricultural output will grow faster than any other countries in next decade, and increasing up to 40% by 2019 (Tollefson 2010). This great economic progress endangers its natural resource reserves, which are not in an adequate balance between growth and sustainability.

In the Southeast of Brazil, the Atlantic Forest is disappearing at an elevated rate. The Brazilian Atlantic Forest originally had over 1.48 million km² (17% of the Brazilian territory) (Ribeiro et al. 2009). Actually only 7% of the original area exists as mostly fragmented remnants distributed over areas difficult to access, such as steep hills and mountainous areas (Vieira et al. 2008). Currently research has demonstrated the importance of maintaining or restoring forest cover in the Atlantic Forest above the 30% threshold to maintain ecological balance (Banks-Leite et al. 2014).

In these areas, the predominant soils are Cambisols (Inceptisols), which constitute very fragile soil systems. These soils are shallow, present a high silt/clay ratio, are very susceptible to erosion and can easily develop crusting (superficial impermeabilization) when vegetative cover is sparse or absent. Because the C horizon is near the surface, extreme care is needed since this horizon has very weak blocky structure when the soil is dry, but when it is moist or wet it has weak expression of the structure, making it extremely susceptible to development of gully erosion. So, these aspects place emphasis on the maintenance of the native forest cover, which increases water infiltration and maintains an adequate and protective soil cover which significantly decrease the potential problems mentioned above. According to Lilly et al. (2012), the influence of the nature and type of horizons within the soil profile and the characteristics of the subsoil are related to the connectivity within the catchment and the overall geomorphological processes in the development of a soil catena; which, these interrelated connections have a profound influence on catchment hydrology. In catchments located in headwater regions, like this study area, the observed responses and relationships are more evident when quantifying groundwater recharge processes (Menezes et al. 2009).

Southeastern Brazil is suffering its worst drought in decades which is threatening hydro-power supplies and potentially slowing economic growth of the country. The expression of the drought was particularly evident in the summer of 2013/2014, where the rainfall season was much lower than average (INPE/CPTEC 2014). According to Energy Company of Minas Gerais State (CEMIG 2014), the Grande River had its lowest streamflow rate in the last 84 years, according to the results from monitoring activities carried out in July, 2014.

In this sense, a better understanding of how water recharges the aquifers responsible for streamflow is necessary so that conservation and management projects can be targeted to strategic locations. Thus, it is possible to minimize the damage caused by variability in climate conditions leading to greater buffering of extreme climate events. Because of this need to understand the relationship and groundwater recharge, there is a need to understand what role the shallow Inceptisols maintain in this process.

Hydropedology is the interweaving of Soil Science and Hydrology, promoting the interface between the pedosphere and the hydrosphere with emphasis on the soils and the associated landscapes (Lin 2012). This field of investigation has great importance for the understanding of soil hydrological behavior under permanent use, especially in headwater landscapes occupied by native forests (Mello and Curi 2012). The authors cite that the investigation of preferential flows has fundamental importance for understanding the processes of groundwater recharge in environments like the UMCF, because the soil is an essential element regulating water cycle functioning, highlighting the storage and transmission water into the saturated zone of the watershed.

More importantly, the influence of land use changes on hydrological processes must be investigated within this region since major land use changes have been observed. It is necessary to obtain a complete understanding of the hydrologic function of the landscape related to the change in land use within areas previously occupied by forests that are being utilized as low productivity pastures (Salemi et al. 2013). This change can provoke significant impacts on the hydrology of the catchments by limiting infiltration and recharge which can alter the base flow behavior due to relationship with the groundwater recharge process.

Further detailed studies to identify the role of Inceptisols and their land use change on water flow through the soil profiles should be priority for Mantiqueira Range for environmental protection. The geomorphological characteristics of this region indicate that this environment is fragile, with shallow soils, steep topography and abundant rainfall. With little knowledge about soil physical changes accompanying forests conversion to pasture, hydropedology can provide information on the soil structure behavior and consequently help understand the soil hydrologic properties in a holistic manner (Mello and Curi 2012).

Therefore, the objective of this study was to understand the role of the shallow Inceptisols of Mantiqueira Range region, Southeastern Brazil, on the hydrology of catchments under pasture and native forest land uses.

Material and Methods

Site Description

The Mantiqueira Range region is one of the most important Brazilian headwater regions, from which several rivers streamflow to feed the most important hydropower plant reservoirs of the country. However, even though there is a highlighted strategic importance of this headwater region, there is not a hydro-weather monitoring network within this region to effectively capture data necessary for the water balance. To overcome that limitation, the Energy Company of Minas Gerais State (CEMIG) and Brazilian Electrical Energy Agency (ANEEL) provided funding for two Research and Development Projects between 2006 and 2012. In these R&D projects, we first selected a geomorphological representative watershed of Mantiqueira's environment (LCW) based on the land use, topography, geology and soils. From this point, in 2006 we installed meteorological stations and a gauging streamflow station in

LCW. Also, there have been other studies related to soil hydraulic conductivity, physical, chemical, mineralogical and micromorphological characterization, and plots for water erosion monitoring. In addition, from 2009 to 2011, a complete data collection in a small catchment entirely occupied by Atlantic Forest in altitudes greater than 1,400 m was installed, with the goal to study how the water-budged functions in this environment. Thus, our scientific effort was carried out to investigate how the groundwater recharge occurs in this environment to generate a substantial scientific knowledge about the interaction between soil – weather – hydrology. We have 7 years of hydro-weather recordings, which is unique, and will be used for the aforementioned projects, which all will lead to a greater understanding of the water yield behavior in Mantiqueira Range region.

LCW is located on the border between Minas Gerais (MG) and Rio de Janeiro (RJ) States, in Southeastern Brazil, within the Mantiqueira Range physiographical region (N 7554590 m, E 553213 m, N 7551260 m, E 558463 m, Geocentric Reference System for the Americas (SIRGAS2000) Universal Transverse Mercator (UTM) coordinate system, Zone 23S). It is a typical headwater watershed, representative of the Upper Grande River Basin, with an important hydro-meteorological regime due to its importance in generating streamflow.

Fig. 1 shows the location of the study area within the Brazilian territory and soil samples locations for this study.

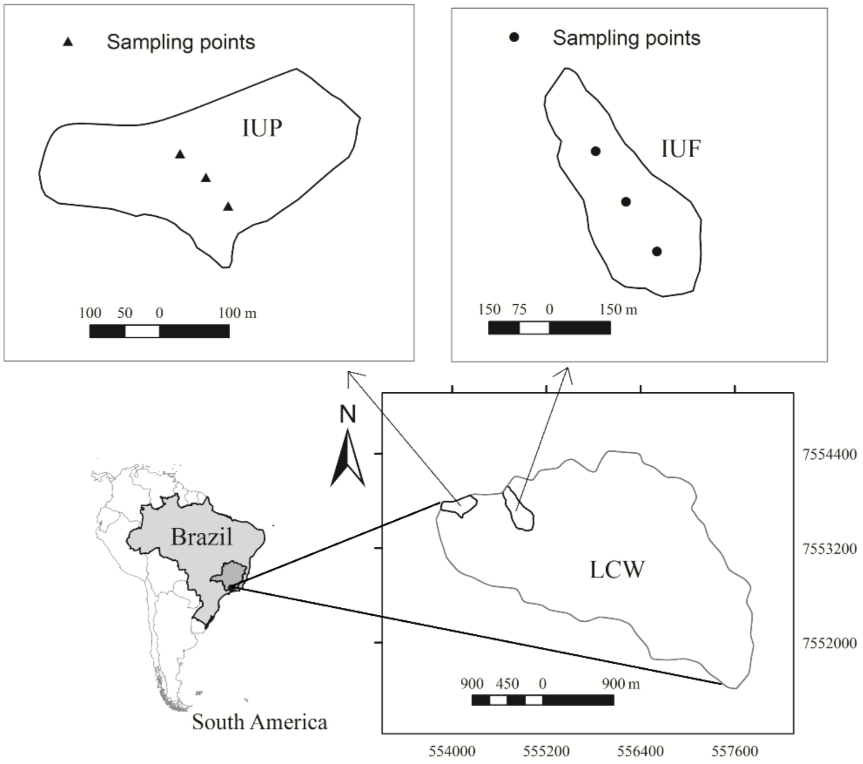

Fig. 1. Geographical location of Lavrinha Creek Watershed (LCW), and soil sampling points for Inceptisols with native forest (IUF) and pasture (IUP) as land use

The parent material of the soils is gneiss, of Neoproterozoic age, whose weathering-leaching processes have resulted in a predominance of shallow Inceptisols, covering 92% of the watershed (Menezes et al. 2009) [Fig. 2(a)]. According to Menezes et al. (2009), the Inceptisols of Mantiqueira Range region are shallow, have moderate permeability and are often gravelly. The use of fire and excessive livestock trampling, results in bare soil, favoring the superficial crusting with all its undesirable consequences, such as accelerated erosion which intensifies the process of degradation of the area. The high silt/clay ratio, coupled with shallow solum thickness (A + B horizons), and low natural soil fertility in mountainous relief make this an unstable and fragile system (Resende et al. 1988).

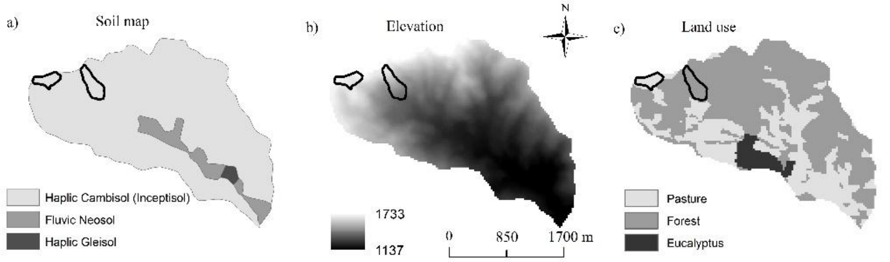

Fig. 2. Soil map, elevation and land use maps of the Lavrinha Creek Watershed (data from Menezes et al. 2009)

LCW covers an area of 676 ha (6.76 km^2), with an elevation ranging from 1137 to 1733 m at the highest ridge [Fig. 2(b)], and it is included in the Andrelândia Plateau (Menezes et al., 2009). The relief is steep with concave-convex hillsides, with average slope varying from 35 to 40%, and a predominance of linear pedoforms and narrow fluvial plains (Mello and Curi 2012; RADAMBRASIL 1983).

The native vegetation is Atlantic Forest (UMCF), and the land cover includes native Atlantic Forest reserve occupying 62% of the area in the steepest slopes, degraded pasture in 33% of the area and *Eucalyptus grandis* plantation in 5% of the area [Fig. 2(c)].

LCW weather characterization

Fig. 3 includes average values for monthly precipitation, potential evapotranspiration, calculated based on Food and Agriculture Organization (FAO) Penman-Monteith method, and air temperature, using data sets from 2006 to 2012.

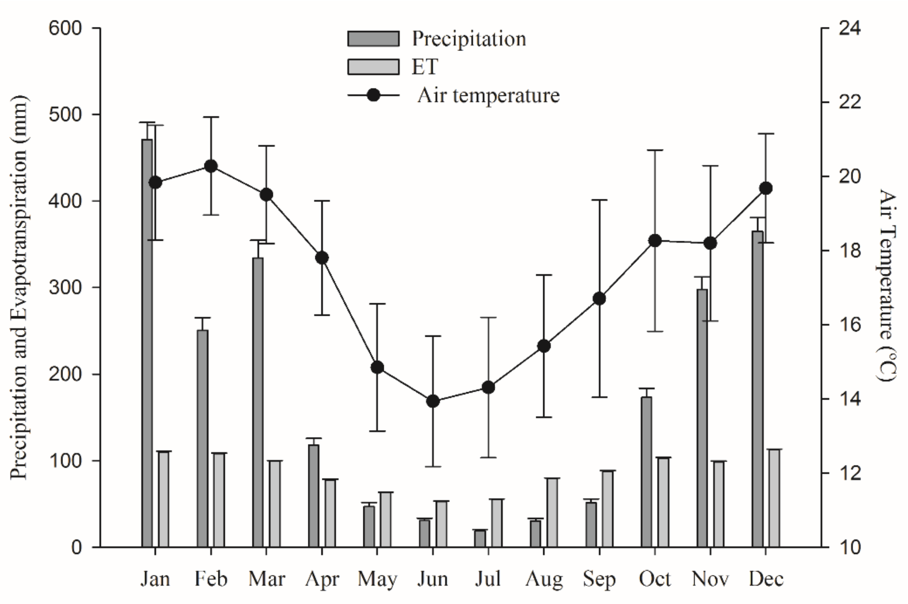

Fig. 3. Average monthly precipitation, potential evapotranspiration (ET), and air temperature observed for Lavrinha Creek Watershed (LCW) from 2006 to 2012

Recent and successful applications of the FAO Penman-Monteith (FPM) (as a base model) for estimation of reference evapotranspiration are currently available (Rahimi et al. 2015; Valipour 2014a, b; Valipour 2015a, b, c, d). These findings justify the choice of the FPM model for our study.

According to Mello et al. (2012), the climate of LCW is Cwb (temperate highland with dry and cool winters and rainy and mild summers) and Hyper-humid A, based on Köppen and Thornthwaite methodologies, respectively. The average annual temperature is 17°C, with minimum and maximum averages, respectively, of 10°C and 23°C. The total annual precipitation ranges from 1841 mm to 2756 mm; on average, 88.3% of the total precipitation occurs between September and March, meaning high rainfall concentration during the summer months. Total annual evapotranspiration ranges from 952 mm to 1180 mm; on average, 68.6% of the total evapotranspiration occurs between September and March.

The Upper Mountain Cloud Forest (UMCF)

A typical Upper Mountain Cloud Forest [Fig. 2(c)] covers a drainage area of 16 ha (0.16 km^2). Its land use consists of a Dense Ombrophilous Forest, which is a typical remnant of the Atlantic Forest of the Mantiqueira Range (Oliveira Filho et al. 2006). The soil has a forest litter layer of an approximately 0.15-m-thick organic layer comprised of decaying leaf litter and other organic materials. The UMCF displays an average slope of 35% and an altitude varying between 1,475 m and 1,685 m above sea level inside IUF (Fig. 1).

The hydro-meteorology instrumentation in UMCF covers the period between June/2009 and September/2011. This monitoring involved measuring the weather parameters with a Campbell automatic meteorological station installed in a clear-cut area outside of the micro-catchment.

Below the UMCF forest canopy, 25 sets of monitoring stations were installed. Each one of these sets was formed by “Ville de Paris” style pluviometers (collected area of 415 cm^2 and installed at 1.5 m from the ground), a tube (1m of length) to access the “Profile Probe” (type PR2/6 Delta-T Devices, London, UK, ±0.13% of accuracy) for soil moisture, and one tree for steam flow measurements. Readings from these instruments were performed manually immediately after every precipitation event, avoiding the accumulation and overlap of rain events.

The streamflow in the outlet of the UMCF was monitored using a Parshall flume attached to a water level logger (model WL16 Global Water Instrumentation, California, USA, with precision of ±0,1%), which provided values every 60 minutes, allowing for continuous characterization of the temporal streamflow behavior.

Soil physical analyses

Soil samples (undisturbed and disturbed) were collected in both micro-catchments with different land uses (native forest and pasture), in three locations along the hillslope: footslope, midslope, and upslope. The sampling depths included 0-20, 20-50 and 50-100 cm with three replicates per soil depth in each trench opened.

The particle size distribution was determined using the Hydrometer Method (Gee and Bauder 1986). Organic carbon was determined according to Walkley and Black (1934) which involves dichromate oxidation technique. Particle density (PD) was determined by the Pycnometer Method (Blake and Hartge 1986a). Analyses of undisturbed samples included: bulk density (BD) (Blake and Hartge 1986b), microporosity (MIC) (Grohmann 1960), macroporosity (MAC), which was calculated from the difference between total porosity (TP) and MIC and, TP was calculated from the values of BD and PD, according to Danielson and Sutherland (1986).

Soil water retention curves were determined in undisturbed soil cores (6.4 cm diameter and 2.5 cm length), and submitted to suctions of 2, 4, 6, and 10 kPa, on fritted-glass Büchner funnels (Vomocil 1965), 33 and 100 kPa in medium pressure chambers; 500 and 1500 kPa in Richard's high pressure chambers, as described by Klute and Dirksen (1986).

The water retained in the soil was quantified and the volumetric moisture was calculated. The soil water retention curves were adjusted by the SWRC software (Dourado Neto et al. 2000) version 2.00, using the van Genuchten (1980) model [Eq. (1)], using the Mualem (1986) mathematical restriction:

$$\theta = \theta r + (\theta s - \theta r)/[1+(\alpha\, \Psi)^n]^m \qquad (1)$$

where, θ is the water content of soil ($m^3\ m^{-3}$), Ψ is the soil water tension (kPa), θs and θr are the saturated water and the residual water contents ($m^3\ m^{-3}$), respectively, and α , m and n are the model parameters.

Micromorphological analyses

Micromorphological studies were made to detail soil porosity. The pore system was characterized using image analysis of thin sections from undisturbed soil samples. Samples for soil micromorphology were collected in three locations in the landscape (footslope, midslope, and upslope positions) and at two depths (0-20 and 20-50 cm) with the

Kubiena boxes covered with plastic film to maintain the structural integrity. The significant and widespread presence of rock (gneiss) fragments hampered the collection of representative undisturbed soil samples at 50-100 cm depth.

The samples were first air-dried and subsequently dried in an oven at 40 °C, 60 ºC and 100 ºC, to reduce cracks in the samples due to a rapid drying. Afterwards, the samples were impregnated with an Avicol® epoxy resin, prepared and de-aerated under vacuum. The impregnated samples were evacuated to remove all air from pores and allow full resin penetration (Castro et al. 2003), and then, heated first (100 ºC during 4 h), and after that (140 ºC during 4 h) to cure and harden the resin. The hardened resin blocks were polished, glued onto glass slides with de-aerated Hillquist® epoxy resin 7A/3B, and heated for 1 min. at 105 ºC. Thus, the samples were sectioned and polished to the ideal thickness and analyzed under a petrographic microscope equipped with polarized light.

Estimated hydraulic conductivity from Flume data

Selected discharge (14) events between September and March from 2009 to 2011, within the LCW and UMCF, covering the rainy seasons were analyzed. This procedure was done in an attempt to cover the entire rainy season in the region and consequently with the soil moisture nearly at saturation. The hydraulic conductivity (K) from the gauging stations (fluviometric station in LCW and Parshall flume in UMCF) data sets was determined based on Darcy's law concept [Eq. (2)] (Mualem 1986):

$$Q = - K\, i\, A \tag{2}$$

where, Q is streamflow that was multiplied by 1.16 x 10^{-8} to obtain the results in $m^3\ s^{-1}$; K is hydraulic conductivity (mm day^{-1}); i is the hydraulic gradient (m m^{-1}); and A is the area (m^2).

If the hydraulic gradient (i) was held constant, then $Q/A = -K$. The hydraulic gradient was represented by the difference in elevation between the gauging station and the highest elevation of the catchment and assumed to be a constant. To satisfy the condition assumed above, only instantaneous peak discharge values were selected during the rainy season, meaning the soils were close to saturation. In this case, the assumptions considered that the soil column throughout the watershed was fully saturated and flows through the "soil column".

Hydrological indicators

To better understand the role of the land use in the maintenance of streamflow, a comparison of hydrology in LCW and UMCF was performed related to base flow behavior at both catchments. For that, the base flow was studied throughout the hydrological years of 2009/2010 and 2010/2011, considering as a hydrological year the period between September of a year to August of a subsequent year.

The hydrological years were studied taking into account the monthly runoff along the periods studied (September/09 – August/11), for both LCW and UMCF. The technique for analyzing the base flow was the Barnes' Method which considers an inflexion point in the hydrograph recession curve (Durães and Mello 2013). This method allowed the characterization of hydrograph recession and, consequently, accounted for base flow and runoff (Db/D), which was the most important hydrological indicator used for comparing the watersheds.

Ávila (2011) conducted a water balance analysis in the UMCF for the two hydrological years considered previously (2009/2010 and 2010/2011), following the mathematical formulation [Eq. (3)]:

$$\Delta S_{UMCF} = \Delta S_{USZ} + \Delta S_{SZ} = Pe - ET - SF \qquad (3)$$

where, ΔS_{UMCF}, ΔS_{USZ} and ΔS_{SZ} are, respectively, the water storage variation in the micro-catchment, in unsaturated and saturated zones, SF is the streamflow, Pe is the external precipitation and ET is the evaporation from the canopy and transpiration from the trees. All the terms in Eq. (3) are in mm.

These results are important to subsidize the hydrological behavior in an environment fully occupied by Atlantic Forest, allowing demonstrating how this catchment can storage water and then become it in base flow.

Results and discussion

Hydrological behavior of LCW and UMCF between 2009 and 2011

The information presented in Fig. 4, represents the selected hydrographs observed in both LCW and UMCF, whose Inceptisols are under native forest (IUF) throughout the hydrological years of 2009/2010 and 2010/2011. In both watersheds, 2009/2010 had greater base flow in the total runoff (Db/D) with 68% and 75.9%, respectively, for LCW and UMCF. In the second hydrological year, the Db/D ratio was smaller, being 57.0% and 62.2%, respectively, for LCW and UMCF. For both hydrological years, a greater amount of base flow to the total runoff could be observed in UMCF, meaning greater infiltration and, consequently, more base flow. However, for the rainy season of 2010/2011, the base flow contribution in the total runoff (Db/D) for both watersheds was smaller due to the occurrence of atypical rainfall period. In this period, more than 900 mm was recorded in January/2011, resulting in a greater contribution of overland flow.

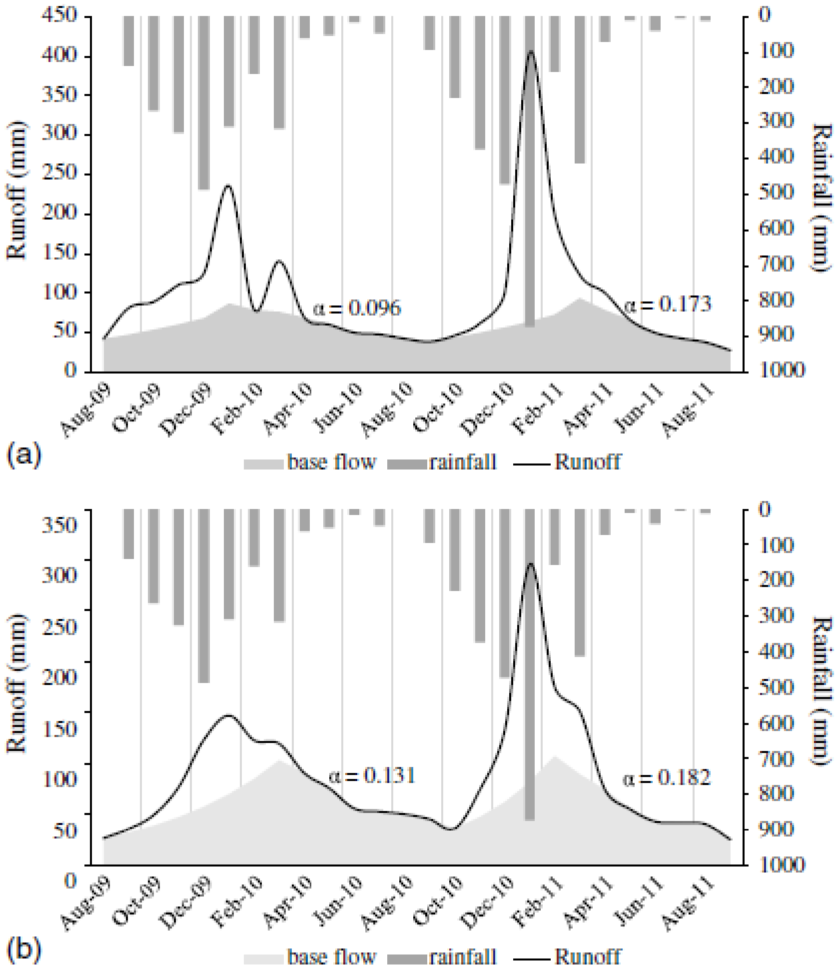

Fig. 4. (a) Base flow results analyze for Lavrinha Creek Watershed (LCW); (b) Upper Mountain Cloud Forest (UMCF) during the water years of 2009/2010 and 2010/2011

Another important hydrological indicator related was the recession coefficient (α) which was, in absolute values, lesser for LCW, in both rainy seasons (0.096 against 0.131 and 0.173 against 0.182, respectively, for 2009/2010 and 2010/2011 hydrological years). This behavior means that UMCF has better conditions to drain water from the aquifer, contributing to base flow in drier periods and producing streamflow more controlled by the groundwater system.

The difference between the rainfall regimes of each hydrological year showed significant intra-annual variability, which is common in tropical and subtropical regions. The rainfall in the second hydrological year tended to be much greater, especially between November 2010 and March 2011. It is important yet to mention that between Sept/01/2011 and Nov/02/2011 there was a total precipitation of 629 mm, corresponding to an average of 26.3 mm day^{-1}, which produced a substantial increase in soil moisture.

Considering that 33% of LCW area is occupied by degraded pasture and 5% by *Eucalyptus grandis* plantation [Fig. 2(c)], this differential land use has a strong influence on the soil hydraulic conductivity in this watershed. Fig. 5 presents the behavior of estimated hydraulic conductivity from the gauging station of both catchments.

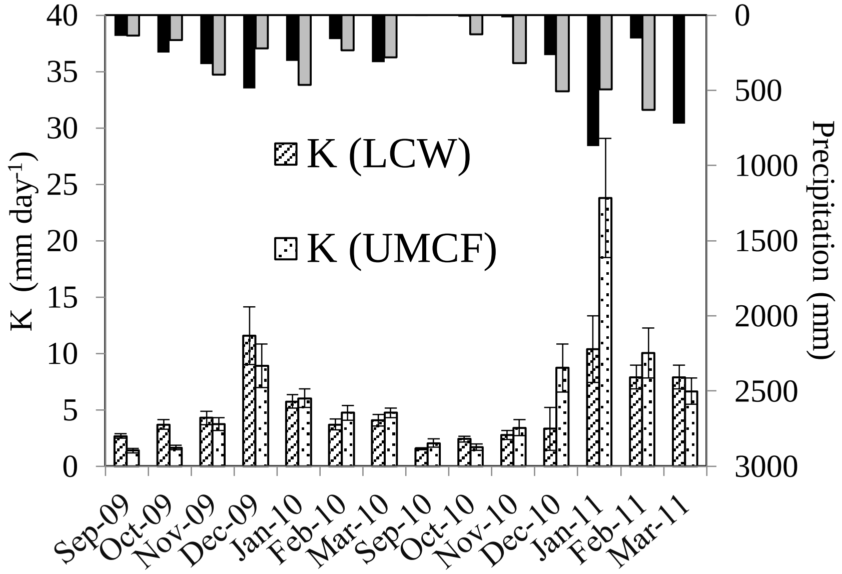

Fig. 5. Estimated Hydraulic Conductivity (K) from the respective gauging stations and rainfall data for LCW and UMCF

The K values were variable and there were greater K values in UMCF in relation to LCW. The K values ranged from 1.6 to 11.6 mm day^{-1} within LCW and from 1.4 to 23.8 mm day^{-1} within UMCF. The rainfall in the second hydrological year tended to be much greater, especially in January 2011.

The maximum daily peak discharges, observed in the UMCF was 0.04 m^3 s^{-1} (21.6 mm day^{-1}) in January 2011, and in LCW was 0.91 m^3 s^{-1} in December 2009. The first discharge occurred in response to 165 mm of rainfall during 4 consecutive hours (41.25 mm h^{-1}), which was one of the greatest rainfall events ever recorded for Mantiqueira Range region. However, this value was lower than that of K values estimated for UMCF, which in this period corresponded to 23.8 mm day^{-1}. Even under this historical rainfall event, the overland flow had little impact on streamflow (Fig. 4). The explanations for this fact are linked to the influence of the mature forest, highlighting the interaction between interception and direct impact of very intense rainfall on the soil surface, and soil hydrological attributes, such as soil saturated hydraulic conductivity and porosity. In this environment, there are conditions favorable for the formation of more effective macropores due to the greater accumulation of organic matter and the lack of human disturbance. According to Roa-Garcia et al. (2011), in tropical and subtropical environments, the hydrological role of forests in the soil hydrological conditions is as important as evapotranspiration demand within the water cycle. This land use provides ideal physical conditions for water infiltration and a subsequent increase of water storage in the saturated zone.

Tobón et al. (2010) found values of K under forest significantly greater ($p < 0.05$) than under pasture for corresponding soil horizons. According to the authors, these results are due to the presence of large macropores and a well-developed soil structure under native forest.

Zimmermann et al. (2006) investigated the effects of land use in areas of the Amazon basin and reported that the more intensive the land use, the more pronounced the decrease in K values. Thus, the overland flow component is more frequent under pasture land use when compared to native conditions or successional forests. These results demonstrate that pasture strongly affects the K values.

Table 1 shows the average daily storage variation in the saturated and unsaturated zones in the Inceptisol with native forest (IUF) for each hydrological year and as an average for the whole period, according to Ávila (2011). It was evident that both hydrological years generated a positive surplus in the catchment, with an increase in the water storage in the saturated zone, highlighting the base flow behavior as shown in Fig. 4.

Table 1. Daily storage variation in the UMCF in the hydrological years of 2009-2010 and 2010-2011

Water Year	ΔS_{SZ} (mm day^{-1})	ΔS_{USZ} (mm day^{-1})	ΔS_{MFO} (mm day^{-1})	P – ET (mm day^{-1})
2009/2010	0.56	-0,26	0.3	2.59
2010/2011	1.08	-0.06	1.02	3.55
Average	0.82	-0.16	0.66	3.07

These results demonstrate the important role of the Atlantic Forest in the behavior of the water movement in the soil profile, favoring better conditions for interception of the direct impact of intense rainfall on the soil surface and better soil hydrologic attributes, such as soil saturated hydraulic conductivity and porosity. This land use also provides better physical conditions for water infiltration and the subsequent increase in the water storage in the saturated zone of soils. This observation was consistent with the lower soil bulk density found under forest as well as the fact that the forest soil presented the greater organic carbon (OC) stocks, which in turn, increases aggregation and pore space, which increases K values (Zimmermann et al. 2006). These results show that the UMCF has higher potential for water infiltration in the surface layer as indicated in Table 1, creating a gradient to move to the saturated zone. Understanding the water dynamics in the soil helps explain the recharge process and, consequently, the reasons for more significant base flow in relation to LCW overall.

Our results justify the importance of conserving the last remaining tropical mountain cloud forest within the Atlantic Forest biome. These results call for a greater attention to the degradation processes occurring in the Mantiqueira Range, especially in relation to the clearing of forests at an accelerated rate, since this was an important environment for conservation of endemic species of flora and fauna, and for maintaining the production of water throughout the hydrological year.

Properties of Inceptisols

Table 2 presents results of bulk density (BD), organic carbon (OC), macroporosity (MAC), microporosity (MIC) and total porosity (TP) for Inceptisols under forest (IUF) and under pasture (IUP). Analysis of these data indicated that BD increased with depth for both land uses. Cooper et al. (2013) cite that the increased bulk density in the subsurface horizons was a natural characteristic of these soils (Inceptisols), due to the greater contents of the clay fraction, organized in a more compact subangular blocky structure.

Table 2. Bulk density (BD), Organic Carbon (OC), Macroporosity (MAC), Microporosity (MIC) and Total Porosisty (TP) of Inceptisol in Upslope, Midslope and Footslope locations

Slope	HL	BD	OC	MAC	MIC	TP
		(g cm^{-3})	(g kg^{-1})	...............(cm^{3} cm^{-3})...............		
Upslope	IUF $_{(0 - 20\ \text{cm})}$	0.90a	45.07a	0.32a	0.31a	0.63a
	IUP $_{(0 - 20\ \text{cm})}$	0.94a	36.78b	0.29a	0.32a	0.61a
	IUF $_{(20 - 50\ \text{cm})}$	0.87b	19.78a	0.30a	0.36a	0.66a
	IUP $_{(20 - 50\ \text{cm})}$	1.14a	16.65b	0.16b	0.39a	0.55a
	IUF $_{(50 - 100\ \text{cm})}$	1.02b	12.32a	0.30a	0.32a	0.62a
	IUP $_{(50 - 100\ \text{cm})}$	1.32a	0.23b	0.10b	0.36a	0.46b
Midslope	IUF $_{(0 - 20\ \text{cm})}$	0.75b	53.37a	0.26a	0.42a	0.68a
	IUP $_{(0 - 20\ \text{cm})}$	1.03a	26.68b	0.25a	0.34a	0.59b
	IUF $_{(20 - 50\ \text{cm})}$	0.93b	23.15a	0.17a	0.46a	0.63a
	IUP $_{(20 - 50\ \text{cm})}$	1.15a	16.65b	0.16a	0.40a	0.56a
	IUF $_{(50 - 100\ \text{cm})}$	1.27a	3.77a	0.18a	0.34a	0.52a
	IUP $_{(50 - 100\ \text{cm})}$	1.36a	3.77a	0.07a	0.41a	0.48a
Footslope	IUF $_{(0 - 20\ \text{cm})}$	0.81b	59.63a	0.38a	0.28a	0.66a
	IUP $_{(0 - 20\ \text{cm})}$	1.20a	26.67b	0.19b	0.34a	0.53b
	IUF $_{(20 - 50\ \text{cm})}$	0.96b	24.89a	0.31a	0.33a	0.64a
	IUP $_{(20 - 50\ \text{cm})}$	1.25a	22.28b	0.23a	0.29a	0.52b
	IUF $_{(50 - 100\ \text{cm})}$	1.00b	6.85a	0.28a	0.36a	0.64a
	IUP $_{(50 - 100\ \text{cm})}$	1.40a	6.21b	0.12b	0.35a	0.47b

Note: Means followed by the same letter, within each depth, did not differ by the Scott-Knott's test ($P < 0.05$).

Regarding land use, the Inceptisols under pasture (IUP) had the greatest BD values. Overall, the mean BD values for Inceptisols under native forest (IUF) were significantly lower than the values obtained for IUP. Price et al. (2010) found BD values 38% higher in soils under pasture and others uses than forest soils. This difference in BD might be ascribed to the compaction of the topsoil due to animal foot traffic on the pastures (Celik 2005), and the lack of an adequate soil conservation management system.

The BD at the 0-20 cm depth upslope in IUP was not significantly different from IUF (Table 2). This result reflects that on summit position of the landscape (upslope), the soil under pasture seems to have a better physical quality than the other landscape positions in the same land use (midslope and footslope). The mean BD values for IUP and IUF in the midslope and footslope were significantly different (with the exception to midslope 50-100 cm depth) (Table 2). In the footslope position, there was an increase of BD with depth in both land use conditions. Cooper et al. (2013) cite that this behavior was associated with a decrease in TP, an increase of clay content and a reduction of OC with depth.

The OC values ranged from 3.77 to 59.63 g kg^{-1} in the IUF and from 0.23 to 36.78 g kg^{-1} in the IUP (Table 2). The greater OC values found for IUF suggest a more protective environment in this condition. In general, the IUF had greater OC values than IUP except at 50-100 cm depth in midslope, where values did not differ statistically (Table 2).

It is important to stress the Inceptisols under pasture (IUP) do not have any soil conservation practices in the area. Considering this situation of degradation, it was observed that the lateral stream erosion of material in the IUP was being exacerbated, highlighting bare soil and crusting, associated with periods of intense rainfall (Mello et al. 2012).

IUF had the greatest values of OC, especially on the surface layer. Menezes et al. (2009) reported the existence of a thick layer of litter on the soils under native forest in Mantiqueira Range, which explains the elevated levels of organic carbon stocks (Table 2). These organic matter contents offer proper conditions for the preferential flows in the soil profile, and, therefore, increases the potential for groundwater recharge and storage. Besides that, OC contributes to protection of soil against direct impact of intense rainfall, increasing the soil capability for water infiltration as well (Menezes et al. 2009). In other words, the greatest amount of organic material on the soil surface, as result of increased root growth and incorporation of litter, and the consequent lower BD values of soils under forest, help to explain such data. Salemi et al. (2013) found higher values of OC in soil superficial layers under forest than under pasture in the Atlantic Forest near Minas Gerais State. According Benites et al. (2007), forests in stable conditions at higher altitude regions and under high average precipitation can favor the accumulation of organic matter when the soils possess medium (loamy) texture and sufficient plant biomass.

The greater OC values and the lower BD values (Table 2) indicated that there was a more macroporosity under forest, due to better conditions for the formation of biopores (Salako and Kirchhof 2003) and subsequent water percolation in soil profile.

Microporosity (MIC) values did not significantly differ at both depth and hillslope position for IUF and IUP. However, macroporosity (MAC) values in IUF were significantly greater than IUP in the upslope (20-50 and 50-100 cm) and in footslope (0-20 and 50-100 cm) (Table 2), possibly due to soil disturbance caused by cattle activity. Gomes et al. (2007), studying the spatial variability of soil physical properties in the

Upper River Grande region, observed that springs inserted through the pasture directly suffer the consequences of grazing around it, with the trampling cattle and utilization of the springs for drink water.

Considering that macropores (pores diameter > 50µm) plays an important role in internal drainage and water recharge into groundwater system, the IUF has better soil physical conditions for an internal drainage and potential recharge.

The porosity usually is determined in relation to the matric potential. In addition, using the soil image analysis, it was possible to see the pore shape and connectivity, providing detailed information on the soil structure (Cooper et al. 2013), helping to understand the movement of water in the soil profile. Pagliai and Kutilek (2008) cite that only a few studies have addressed the characterization of soil porosity and the role in water movements in soils although soil hydrological functions are strongly dependent on the soil porous system.

The total porosity values (TP) in IUF were significantly greater than in IUP in the midslope and footslope (0-20 cm) (Table 2). Tobón et al. (2010) found significant differences in porosity between forest and pasture, and they associated it with cow trails and no trail surfaces. These results demonstrate that IUF has a greater potential for the water percolation from surface layer to saturated zone, helping to explain the recharge process and base flow behavior in this environment. According to Hümann et al. (2011), soils with mature native forest cover display a high degree of porosity, where these soils have a high capacity for water infiltration and a consequent reduction of overland flow.

The soil water retention curve shapes (SWRCS) are presented in Fig. 6. In these curves, macropores can be separated from micropores at the water matric potential of - 6 kPa and the soil moisture can be called “field capacity” (FC), although it has a dynamic behavior (Ferreira and Marcos 1983).

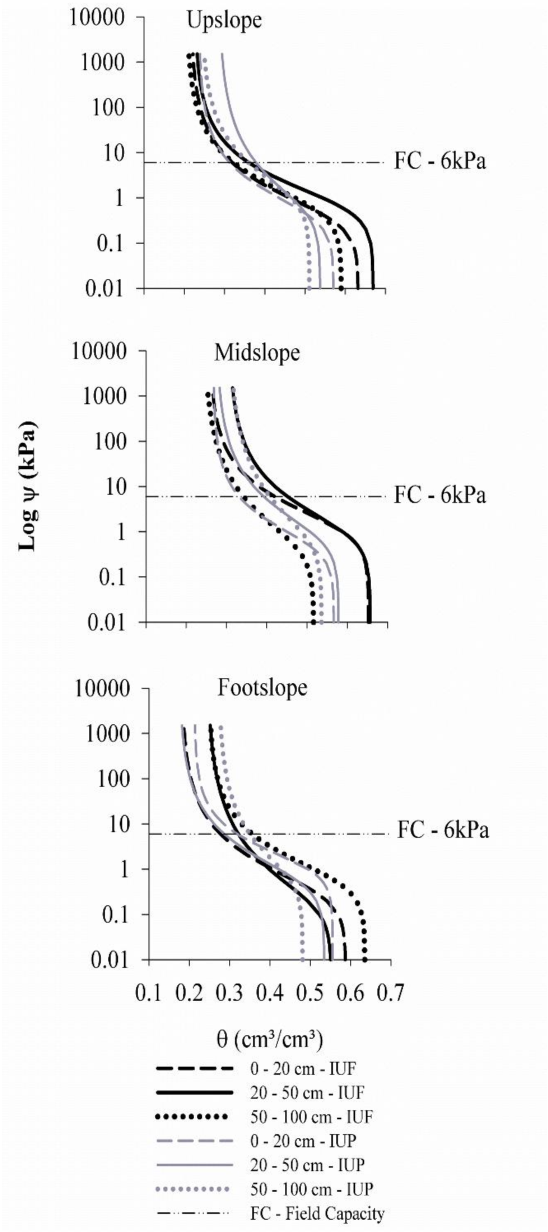

Fig. 6. Inceptisols water retention curves in two situations of land-uses (IUF and IUP) at different depths, for Mantiqueira Range conditions

The SWRCS indicated that the Inceptisols under forest contained more macropores, which are very important for water movement in soil profile under saturation condition. Linking Table 2 and Fig. 6, the IUF presented a dominance of porosity, especially in the surface layers. This trend was less clear in IUP, implying fewer macropores. These results demonstrate that in IUF has the potential to drain water quickly and was, therefore, less water was retained in the upper soil layers.

Tobón et al. (2010), comparing SWRCS for forest and pasture soils, showed that, beyond water availability that is greater in the forest for most depths, the values of water retained at FC adopted in their study (-33kPa) are always greater than in the pasture. In our study, we found larger micropores in the pasture than in the forest, adopting -6 kPa separation (Ferreira and Marcos 1983). These greater MIC values in the pasture are associated with the higher BD values for IUP than for IUF (Table 2). The largest volume of water retention for IUP does not necessarily imply greater availability of water, particularly with respect to groundwater recharge. Given that Inceptisols in the Mantiqueira Range region are shallow, the topography is mountainous and the rainfall is abundant, the soil unsaturated zone has a limited storage capacity. These conditions promote water percolation into the saturated zone, thereby increasing the storage potential of the saturated zone. Therefore, it was expected better conditions for water recharge into the IUF’s soil profile, indicating it has a greater potential for water percolation beginning in the surface layer to the saturated zone.

Micromorphological analyses

Micromorphological analyses of the Inceptisols studied were conducted to further understand soil porosity behavior and water percolation into saturated zone (Fig. 7).

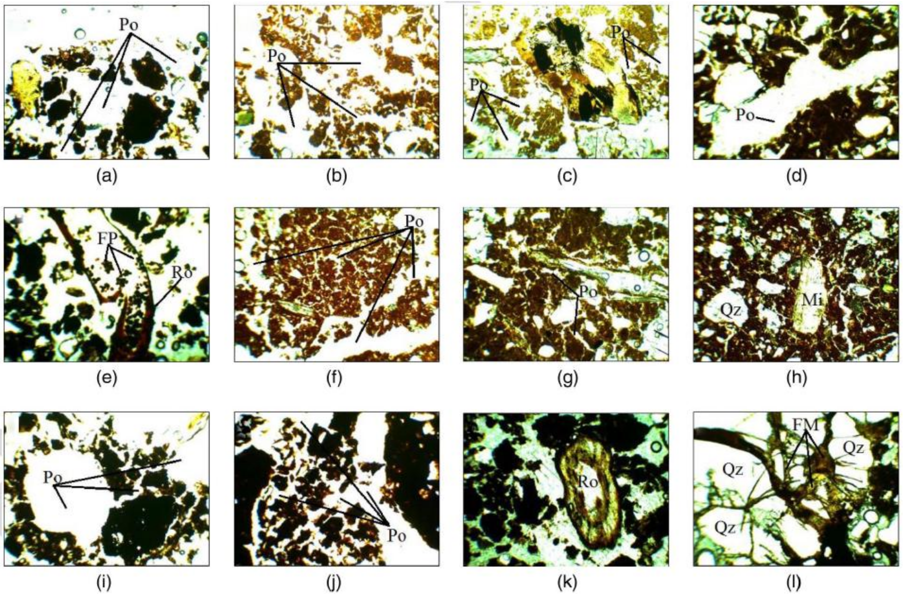

Fig. 7. Selected micrographs of IUF in upslope position at (a) 0-20 and (b) 20-50 cm depths; IUP upslope at (c) 0-20 and (d) 20-50 cm depths; IUF midslope at (e) 0-20 and (f) 20-50 cm depths; IUP midslope at (g) 0-20 and (h) 20-50 cm depths; IUF downslope at (i) 0-20 and (j) 20-50 cm depths; IUP footslope at (k) 0-20 and (l) 20-50 cm depths (note: Po = porosity, FP = faecal pellets, Mi = Mica, Qz = Quartz agglomerates with pedogenic intrusion with fine material (FM) in the cracks and Ro = roots. All frames are 2.3 mm wide and under planar polarized light)

Such study corroborated the patterns obtained for porosity analyses based on soil physical parameters (Table 2). Images of IUF show blocky structure, where the aggregates are separated and surrounded by elongated continuous pores well developed, while the IUP images show few interconnected pores with some isolated pores surrounded by many minerals in the coarse fraction, and semi-weathered rock fragments (Fig. 7). This connectivity decreased with depth for IUP because of the decrease in TP (Table 2) where at 20-50 cm depth the soil aggregates are surrounded by quartz agglomerates with pedogenic intrusion with fine material (FM) in the cracks [Fig. 7(l)].

The microstructure in the surface layer of IUF was strongly affected by organic matter accumulation, with roots surrounded by faecal pellets [Fig. 7(e)] from biological origin (Phillips and FitzPatrick 1999).

Fig. 7 demonstrates the moderately and poorly developed structure of Inceptisols (Resende et al. 2014), highlighting those under pasture with less developed structure. This very weak structure leads to major environmental damage in terms of exposure of these soils with low biological production vegetation, to erosion and less opportunity for water infiltration. Hence, the importance of forest for protection of Inceptisols, especially in mountain slopes, such as those occurring in the Mantiqueira Range region, is evident.

Pagliai and Kutilek (2008) found a significant correlation between the elongated continuous transmission pores and the saturated hydraulic conductivity, showing that the shape, the size, the orientation and the continuity of pores regulate water movement in the soil profile. These results reinforce the role of micromorphology analysis in conjunction with other soil analyzes to characterize in details how the Inceptisols influence water recharge processes. Such studies are scarce, especially in the mountainous regions of Southeastern Brazil.

Conclusions

This study indicates that land use has a significant impact on the hydrologic behavior of soils within the Lavrinha Creek Watershed (LCW) in Brazil. There was a greater portion of base flow when compared to the total runoff in Upper Mountain Cloud Forest (UMCF), when compared to the base flow of the entire LCW. The UMCF had better conditions for water infiltration and groundwater recharge to provide discharge water to produce streamflow into drier periods.

The micromorphological study showed a remarkable decrease of macroporosity in the pasture, which resulted in decreased rates of water infiltration, decreased hydraulic conductivity and decreased total porosity. These data provided useful supporting information on the soil pore system and together with hydrological and other soil properties of the watershed helped in understanding the processes of water recharge.

This study indicates that soil properties are related to the dynamic nature of hydrologic events; however, land use is also very important. Watersheds with minimal disturbance will function to store water within the soil and groundwater systems due to the ability to capture and store water after a precipitation event. There should be increased focus on conservation practices that enhance water infiltration and water storage to buffer in landscape systems for normal and extreme climatic events.

Acknowledgments

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PAPER 3

Spatial Prediction of Soil-water transmissivity based on fuzzy logic in a Brazilian headwater watershed

Normas da Revista: Catena (versão preliminar)

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Abstract: The Mantiqueira Range region is one of the most important Brazilian headwater regions, from which a great number of springs flow to form one of the most important watercourses for São Paulo, Rio de Janeiro and Minas Gerais States. These natural features make the Mantiqueira Range an important

hydrological region for research and development of technologies for management and environmental preservation. Areas in which the predominant land-use is native forest have proved to be strategic for groundwater recharge purposes, and thus, to mitigate drought effects that are being observed recently in Southeastern Brazil. In this context, to identify and map these areas leads to better and more successful decision making regarding soil-water conservation and management. In headwater watersheds, the knowledge about spatial distribution of soil-water transmissivity can be very important to sustainable use and conservation of environmental resources. The aim of this study was to evaluate the application of pattern recognition on landscape classification tools combined with digital soil mapping techniques for mapping soil-water transmissivity in a watershed located at one of the most important Brazilian headwaters, in Southeastern Brazil. Validating the modeling approach based on hydro-climatic monitoring allowed the soil-water transmissivity distribution for the entire watershed to be obtained. The model used solum depth and saturated hydraulic conductivity as soil deterministic elements and topographic indexes. The results showed that the method proposed combining terrain attributes and Geomorphons, which is a mapping tool that allows for the identification of landforms within a landscape through digital elevation model analysis, was very efficient and, therefore, used to predict the soil-water transmissivity for the watershed. Areas with high to moderate soil-water transmissivity values were associated with the steepest slopes, shallow and moderately deep Inceptisols and native forest fragments. Since the relief and solum depth features of Inceptisols did not show optimal conditions for soil water percolation, the results demonstrated that land-use and management factors are crucial for groundwater recharge in the region of the Mantiqueira Range. In order to support these findings, we have observed compatible hydrological indicators in the studied area. Considering that the studied micro-catchment is entirely covered by native

forest and has presented greater values of soil-water transmissivity, this watershed was supported by greater base flow/runoff ratio, and a greater capacity to maintain the base flow in drier periods, and thus, a more stable groundwater recharge system. The results also showed that areas with native forests play a fundamental role in water distribution processes in the soil profile in mountainous catchments in Southeastern Brazil. These results strengthen the importance of soil conservation practices and adequate land-use to sustain this kind of environment in Brazil.

Keywords: Atlantic Forest; hydropedology; Mantiqueira Range; water recharge

1. Introduction

The soil-water transmissivity indicates the ability of soils to transmit water through its entire saturated thickness. Its importance is strongly linked to groundwater recharge, mainly in headwater watersheds. Thus, the understanding how this soil attribute's behavior in the watershed can be very important to support sustainable uses and conservation of environmental resources.

Since the end of 2013, Southeastern Brazil is suffering with one of the worst droughts recorded (Coelho et al., 2015a, 2015b). Various harmful effects from climate change impacts, such as change in the dynamics of wind and clouds, can influence rainfall patterns in southeast and mid-west Brazilian regions (Arraut et al., 2012; Nobre, 2014). In addition to that, there are several possible other reasons for this hystorical drought as the climate system is interconnected with the physical, chemical and biological features of the planet. In this context, we can highlight possible impacts from global warming, Amazon Forest deforestation, which is implicated in a decrease in moisture avalaibility, and seasonal global circulation phenomena that affects weather patterns, like those related to ENSO (El-Niño Southern Oscillation).

More specifically, another reason for these pronounced drought effects is related to Atlantic Forest deforestation in Mantiqueria Range region, as this ecosystem plays a fundamental role in the hydrology of the region, whose sustainability could mitigate a number of consequences derived from this precipitation deficit anomaly.

The Atlantic Forest was one of the largest rainforests of the Americas (Ribeiro et al., 2009), however, today it covers only 7% of the original area in mostly fragmented remnants distributed over areas with difficult access (Vieira et al., 2008), such as very steep hills and mountainous areas like Mantiqueira Range region.

The deforestation of the Mantiqueira Range region has caused a fast reduction of the natural regulation of streamflow, leading to scarce water and more frequent drought (Menezes et al., 2009; Viola et al., 2015). In Mantiqueira Range, there are many springs condensing and forming great rivers which are the most important streamflows sources for São Paulo, Rio de Janeiro and Minas Gerais States. Thus, this geomorphological environment is the most important headwater region of Southeastern Brazil, being one of the most important areas for groundwater recharge and surface water supply to this region.

These features make the Mantiqueira Range an important region for research and development of technologies for management and environmental preservation. Whereas, groundwater recharge in the Mantiqueira Range region is sensitive to use and management of soils (Alvarenga et al., 2012; Menezes et al., 2009), the areas where the predominant land-use is native forest have proved to present better conditions for groundwater recharge, and thus, to mitigate the effects from possible global warming impacts. In addition, factors linked to soil management practices are crucial for groundwater recharge in the Mantiqueira Range region. Mapping of more conductive areas for groundwater recharge leads to better and more successful decision making regarding conservation and soil water management. In this sense, the knowledge of the distribution of soil-water transmissivity becomes a very important practical tool for management of watersheds in headwater regions. The spatial identification of promising areas in the context of water recharge allows for better land-use planning in order to maintain a sustainable water supply (Viola et al., 2015).

Recently, several studies concerning distribution of soil properties has been published from environmental variables like terrain attributes (Ashtekar and Owens, 2013; Greve et al., 2012; Menezes et al., 2014; Silva et al., 2014; Silva et al., 2015) and landform classification derived from a digital elevation model (Iwahashi and Pike, 2007; Jasiewicz and Stepinski, 2013). In Mantiqueira Range, where the relief is very steep (Menezes et al., 2014), landform classification is very important for understanding several hydrological processes, especially those related to rainfall-runoff and infiltration capacity which are both deterministic for groundwater recharge.

Iwahashi and Pike (2007) proposed a landform classification method characterized as unsupervised. This method uses slope gradient, surface texture (surface roughness) and local convexity derived from a DEM for automatic classification of topography. Yet, according to these authors, this empirical approach considers topography as a continuous random surface, independent of any spatial or morphologic orderliness imposed mainly by fluvial activity or other geomorphic processes. Slope gradient, surface texture (surface roughness) and local convexity are calculated within a given window size and classified according to the inherent data set properties, being characterized as a dynamic landform classification method (Barka et al., 2011). Among the advantages of this method, are applicability to any landscape, adaptation to a DEM with any spatial scale or extent, computational efficiency, and results agreeable with geomorphological interpretation (Iwahashi and Pike, 2007).

Jasiewicz and Stepinski (2013) performed another landform classification, called “Geomorphons”. The Geomorphons is a mapping tool that identifies landforms within a landscape through Digital Elevation Model (DEM) analysis. This tool has little computational cost and utilizes the concept of Local Ternary Patterns (LTP) (Liao, 2010), where a local pattern is determined using a neighborhood with size and shape that self-adapts to the local topography. From a typical terrestrial landscape, the most frequent and commonly landform elements used in many geomorphology classifications according to Jasiewicz and Stepinski (2013) are: flat, peak, ridge, shoulder, spur, slope, hollow, footslope, valley, and pit.

With the advances of computational sciences, researchers have increasing access to DEM, available at different resolutions, which can aid in relating soils differentiation based on relief, soil expert knowledge, and mapping techniques, such as fuzzy logic (Menezes et al., 2013; Silva et al., 2014). Its application in a hydropedological context can be a very promising tool, helping the understanding of how the water interacts with landscape features.

Soil attributes can be predicted using fuzzy logic, similarity vectors (Zhu et al., 1997) and a software package for knowledge-based raster soil mapping (Shi et al., 2009). Fuzzy logic has shown good performance for soil mapping, and prediction of their attributes (Zhu and Band, 1994; Zhu et al., 1997, 2001; Zhu and Lin, 2010) and has been successfully applied in the prediction of soil-water transmissivity (Zhu et al., 1997). This method is based on the premise that the knowledge of a soil scientist and an understanding of soil-landscape relationships act as a model to predict classes and soil properties (Ashtekar and Owens, 2013; Silva et al., 2014).

Zhu et al. (1997) cite that soil-water transmissivity has high spatial variability in a very short distance, therefore, being difficult to map accurately. The same authors used a set of GIS techniques and a fuzzy inference engine, and demonstrated the usefulness of this fuzzy representation for soil-water transmissivity, finding better results for mapping in steep mountainous region when compared with gentle and steep slopes.

According to Menezes et al. (2013), techniques for digital soil mapping based on the use of fuzzy logic allow a faster production of a soil survey, and continuously adjusts the spatial distribution of soil properties into discrete categories according to the complexity of the variability of them, increasing the accuracy of information in space.

In this context, the knowledge about the local of the landscape associated with each soil type can define the soil-water transmissivity in a portion of a given soil toposequence. The combination of a landform classification tool together with the hydropedological attributes like soil saturated hydraulic conductivity and solum depth will increase our knowledge about the process of soil water infiltration, and thus, the groundwater recharge in a headwater watershed.

The overall hypothesis for this research is that landforms associated with solum depth, hydrologic attributes and land-use mapping have strong influence on soil-water transmissivity in watersheds within a headwater environment, like the Mantiqueira Range region, where the groundwater recharge processes are sensitive to land-use (Alvarenga et al., 2012; Viola et al., 2013).

The objective of this study was to evaluate a modeling process based on a pattern recognition application using landscape classification tools combined with digital soil mapping techniques for mapping soil-water transmissivity in a watershed located in the Mantiqueira Range region, Southeastern Brazil. This project hoped to validate the objective using hydro-climatic monitoring and soil saturated hydraulic conductivity observed in situ through a consistent sampling scheme.

2. Materials and Methods

2.1 Study area remarks

The Lavrinha Creek Watershed (LCW) is located on the border between Minas Gerais and Rio de Janeiro States, in Southeastern Brazil headwaters, within the Mantiqueira Range physiographical region. This watershed covers an area about 676 ha, with elevation ranging from 1137 to 1733 m at the highest ridge. It is included in the Andrelândia Plateau and parent material of soils is gneiss from Neoproterozoic (Menezes et al., 2009). The massive rock gneiss in this region is fractured, thus contributing for storage and transmittance of water capacity (CETEC, 1983). The relief is steep, concave-convex hillside, average slope from 35%, with a predominance of linear pedoform, and narrow fluvial plains (CETEC, 1983; Mello and Curi, 2012; RADAMBRASIL, 1983).

For preparing a thematic map of land-use in the studied area, an image of Landsat 8 OLI (Operational Land Imager) was employed. This map was obtained based on an object-oriented classification method using eCognition software. For image segmentation, the multi-resolution algorithm described by Baatz and Shäpe (2000) that used criteria of homogeneity, and a scale parameter defined complex objects that make up the landscape.

The native vegetation is Atlantic forest, and land cover include Atlantic Forest occupying 62% of entire LCW in the steepest slopes, degraded pasture in 33% and *Eucalyptus grandis* plantations are 5% area (Fig. 1).

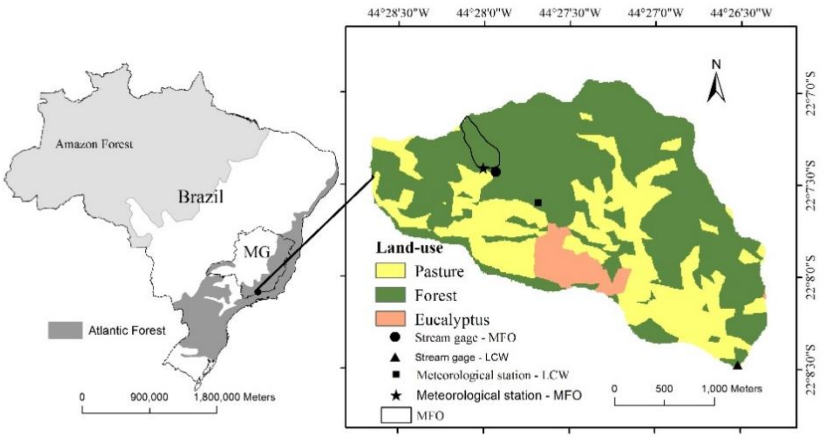

Fig. 1. Geographical location and land-use map of Lavrinha Creek Watershed (LCW) with a micro-catchment entirely covered by native forest (MFO) in Mantiqueira Range, Minas Gerais State (MG), Southeastern Brazil.

Inceptisols are the main soils of the watershed, covering about 92% of the area. They are moderately drained and present C horizon near of the surface, making it extremely susceptible to water erosion. These soils have very weak blocky structure when the soil is dry, but when moist or wet there is no expression of such structure. Also they are very susceptible to crusting, which tends to decrease the natural low water infiltration. These aspects make these soils very fragile systems.

2.2 DEM and Environmental variables

From planialtimetric maps (1:50,000 scale) and elevation points available at the IBGE website (http://www.ibge.gov.br), a digital elevation model (DEM) was generated (Fig. 2) with pixels of 10 x 10 m for LCW, which were delineated using ArcGIS software (ESRI, 2014). The sinks were filled and a hydrologic consistent DEM was created.

Three sets of environmental variables were used, being terrain attributes and two different landform classifications – Geomorphons (Jasiewicz and Stepinski, 2013) and the method proposed by Iwahashi and Pike (2007). The DEM was used to develop environmental variables, terrain attributes (altitude, slope, profile curvature, plan curvature and SAGA wetness index), and the landform classifications.

2.3 Terrain Attributes method

Terrain attributes (TA) were developed by differential geometry calculated from the DEM using SAGA GIS 2.0.6 (Böhner et al., 2014) and an ArcGIS extension ArcSIE (Soil Inference Engine), version 10.1.002 (Shi, 2014) (Fig. 2). The attributes taken into account were: altitude, slope that is the gradient of elevation; profile curvature that is the slope shape in the direction of the maximum slope and is, therefore, associated with water flow; plan curvature that is the slope shape perpendicular to slope direction, which measures the convergence or divergence and, hence, the concentration of water in a landscape (Moore et al., 1993); and SAGA wetness index (SWI) that is a wetness index similar to the topographic wetness index (ln(a/tanb)), where a is the ratio of upslope contributing area per unit contour length and b, the tangent of the local slope. Although these wetness indexes appear to be similar, SAGA has an advantage the capability for adjusting the width and convergence of the SWI multidirectional flow to a single directional flow (Menezes et al., 2014).

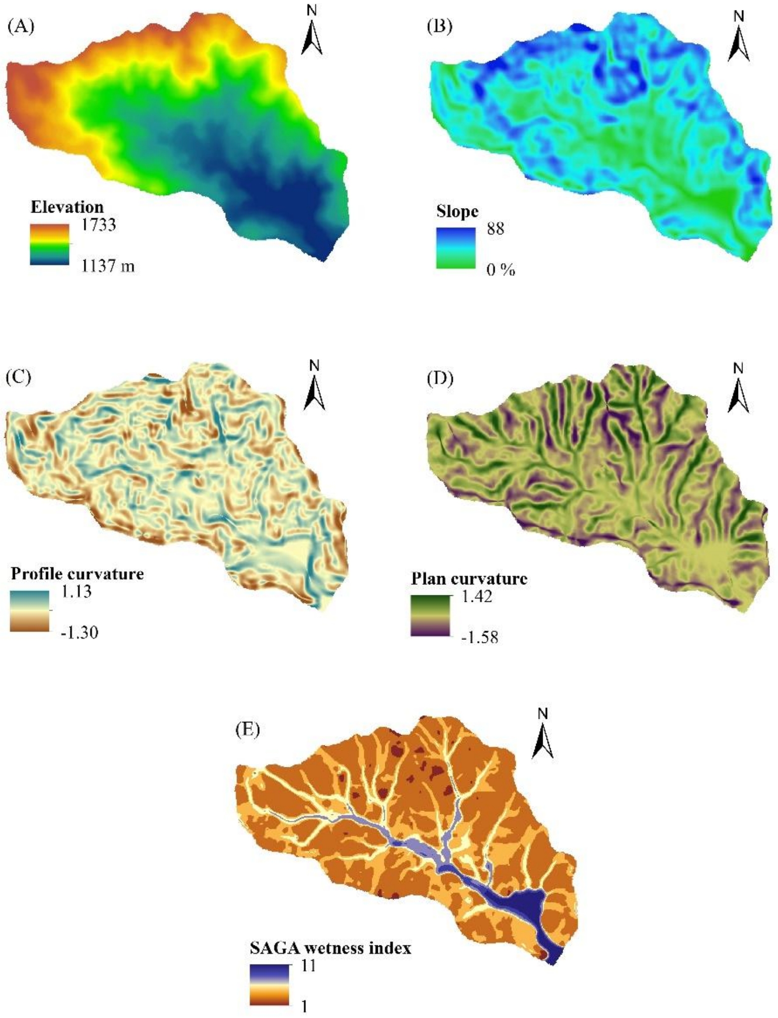

Fig. 2. Terrain attributes: elevation (A), slope (B), profile curvature (C), plan curvature (D) and SAGA wetness index (E) for LCW.

2.4 Landform classification

The unsupervised method developed by Iwahashi and Pike (2007) was implemented using ArcSIE (Soil Inference Engine) version 10.1.002, a toolbox that functions are in Arcmap extensions (Shi et al., 2009). This methodology uses slope gradient, surface texture and local convexity derived from a DEM for automatic classification of topography. The surface texture used for this method was measured as the total number of pits and peaks in the neighborhood of a cell (Shi, 2014). However, the ArcSIE uses only DEM and slope gradient layers for the landform classification and all other intermediate factors used by the algorithm are automatically created during the process (Shi, 2014).

Another landform classification method used was Geomorphons. This landform classification is based on the concept of local ternary patterns (LTP) (Liao, 2010). In the LTP, a neighbor is labeled 1 if its value exceeds the value of the central cell by at least t where t is a specified value of threshold; a neighbor is labeled −1 if its value is at least t lesser than the value of the central cell and, otherwise, the neighbor is labeled 0 (Jasiewicz and Stepinski 2013).

Geomorphons was derived from DEM using look up distance (L) of 60 cells (or 600 m) and flatness threshold (t) of 1 degree. The classification of landform was performed using GRASS GIS 7.0 (Neteler and Mitasova, 2008).

2.5 Soil saturated hydraulic conductivity (Ksat)

Soil saturated hydraulic conductivity (Ksat) were determined in situ using a constant flow permeameter (Ghelph permeameter - model 2800KI), totaling 198 points which were sampled in LCW's area following a regular grid of 300 x 300 m, with refining scale of 60 x 60 m and another refining of 20 x 20 m, and two transects with the distance of 20 m between points (Fig. 3).

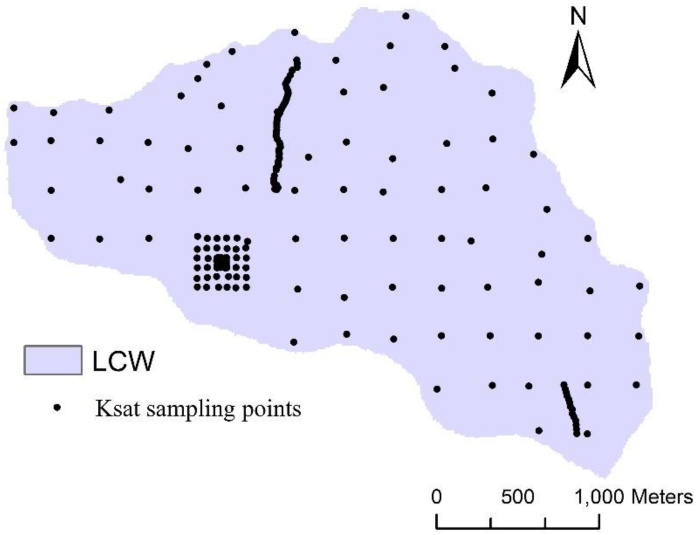

Fig. 3. Ksat sampling points for LCW.

2.6 Solum depth (SD)

The solum depth map (thickness of A + B horizons) was obtained from Menezes et al. (2014). In order to obtain the solum depth, three steps were taken by Menezes et al. (2014). (1) Establishment the soil-landscape relationships to predict soil classes, where this step was the basis for setting rules and was based on the soil scientists' knowledge, maps from previous soil surveys and other types of soil research developed at the study site. (2) Quantification of relationships between soils and terrain attributes and formalizing these relationships in a set of rules in an ordered array of numbers that represents the spatial distribution of terrain attributes across a landscape, in a raster-based format. (3) Solum depth map implementation, based on fuzzy membership values, where the continuous variation of soils could be represented by continuous solum depth derived from similarity vectors (Zhu et al., 1997). In other words, these results of solum depth were derived from a soil survey where each soil mapping unit assumes a unique value based on the soil profile described and sampled, which represents a central or modal concept for that soil mapping unit (Menezes et al., 2014).

2.7 Soil properties map

For the models' development, a set of rules for the entire watershed was inserted in an ArcGIS 10.2 (ESRI) extension, named ArcSIE (Shi, 2014). This set was established based on the experience and expertise accumulated with different studies in the Mantiqueira Range region since 2006. From these, we can highlight soil surveys, classification and mapping, characterization of the soil physical properties, such as particle size distribution, water retention curves, in situ hydraulic conductivity and soil moisture measurements, and hydro-climatic data set monitoring (Alvarenga, 2010; Araújo, 2006; Ávila, 2011; Junqueira Júnior, 2006; Menezes, 2007, 2011). All these studies are inserted within the scope of Research and Development projects sponsored by Minas Gerais State Electric Energy Company (CEMIG) and National Agency of Electric Energy (ANEEL) in the context of watersheds management research.

The soil inference engine (SIE) is an expert knowledge-based inference tool designed for creating soil maps based on fuzzy logic (McKay et al., 2010), setting a similarity value for each pixel ranging from 0 (no similarity) to 1 (high similarity).

The values of the environmental covariates and ranges associated with each soil type were used to define membership functions, which in turn are referred to as optimality functions because they define the relationships between the values of an environmental feature and a soil type (Menezes et al., 2013).

The threshold values are identified and assigned to each soil map unit in a GIS environment. For this, data layers in a raster format that characterize environmental covariates (Shi et al., 2009) as terrain attributes and landforms classification were prepared.

Three combinations of the environmental variables (Terrain Attributes (TA), Iwahashi and Pike (2007) (IP) and Geomorphons (GM)) were tested for predicting Ksat. (1) TA, (2) TA + IP and (3) TA +GM.

For Ksat, the samples were shared into two groups, one for training and another for validation of models. Data from the training group were used to generate predictive models for Ksat while for validation, it used 20% of the data.

The relationships between soil and terrain attributes were quantified using an ordered array of numbers that represent the spatial distribution of terrain attributes across a landscape in a raster-based format (Bishop and Minasny, 2005) for ArcSIE.

Based on fuzzy membership values, the continuous variation of soil properties could be derived from similarity vectors, using the following formula (Zhu et al., 1997) (Eq. 1):

$$\mathrm{V_{ij}} = \frac{\sum_{\mathrm{k=1}}^{\mathrm{n}} \mathrm{S_{ij}^{k}} * \mathrm{V^{k}}}{\sum_{\mathrm{k=1}}^{\mathrm{n}} \mathrm{S_{ij}^{k}}} \tag{1}$$

where V_{ij} is the estimated Ksat value at location (ij), $\mathrm{S_{ij}^{k}}$ is the final fuzzy membership value at (ij) for soil type k, V^{k} is a typical value (mean) of soil type *k*, and *n* is the total number of prescribed soil types for the area.

2.8 Assessment of prediction methods

The prediction of Ksat maps was assessed by comparing the predicted Ksat values with the correspondent values from the validation set using R^2, mean absolute error (MAE) and root mean square error (RMSE) (Willmott, 1982). MAE and RMSE have the formulas below (Eq. 2 and 3) respectively, considering the better model that with greater R^2, MAE values nearer to 0 and lesser RMSE.

$$MAE = \frac{\sum_1^n |O - S|}{n} \tag{2}$$

$$RMSE = \sqrt{\frac{\sum_1^n (O - S)^2}{n}} \tag{3}$$

where: n is the number of validation points, O is the observed Ksat value determined in situ by the constant flow permeameter and S is the simulated Ksat value by the Fuzzy logic model.

2.9 Soil-water transmissivity concept (T)

The Ksat soil hydraulic property and solum depth were used in the analysis of soil-water transmissivity (T) in the watershed. After choosing the best method for Ksat prediction, soil-water transmissivity for the watershed could be determined.

T values were obtained based on the Ksat and SD maps, which were predicted using the digital soil mapping equation adapted from Montgomery and Dietrich (1994) (Eq. 4):

$$T = Ksat \times SD \quad (4)$$

where: T is the soil-water transmissivity, in m^2 day^{-1}; Ksat is the saturated hydraulic conductivity, in m day^{-1}, and SD is the solum depth in meter.

2.10 Hydrology background

In order to validate and better understand soil-water transmissivity behavior, some hydrological indicators were performed based on comparison between base flow (BF) behavior in a micro-catchment entirely occupied by native forest located inside LCW (MFO) and in LCW as a whole, as the latter has its hydrology influenced by other land-uses (Fig. 1). BF is directly related to groundwater recharge and water storage in the underground saturated zone of the watersheds and thus, dependent of T behavior.

MFO covers a drainage area of about 16 ha with 100% of its area occupied by Dense Ombrophilous Forest, which is a typical remnant of the

Atlantic Forest of the Mantiqueira Range region (Oliveira Filho et al., 2006). This micro-catchment displays an average slope of 35% and an altitude varying between 1,475 m and 1,685 m above sea level.

Weather data sets at LCW and MFO covers the period between June/2009 and September/2011, with one Campbell automatic meteorological station installed at the site. Streamflows were monitored using a Parshall flume attached to a water level logger (model WL16 Global Water Instrumentation, California, USA, with precision of ±0,1%), which provided values every 60 minutes, allowing for a continuous characterization of the temporal streamflow at MFO. For LCW, the same device was employed, however, building a gauging station and fitting a discharge curve for the section throughout time.

Base flow was studied throughout the hydrological years of 2009/2010 and 2010/2011, considering as a hydrological year the period between September of a year to August of the subsequent year as the region is strongly characterized by a rainy summer and a dry winter (Mello et al., 2012). Its characterization was made based on the separation from streamflows (direct surface runoff and base flow from total runoff). For that, daily streamflow observations from 2009 to 2011 were used and the Barnes' method was applied allowing the characterization of hydrograph recession (Barnes, 1939; Durães and Mello, 2013; Hingray et al., 2014). This method is based on the identification of inflex points in the flood hydrographs, considering an exponential behavior for the base flow (Equation 5). From the separation of the base flow, it is possible to account for it in relation to the total runoff (Db/R), which is one of the most important hydrology indicators used for comparing watersheds.

Recession coefficient was defined following the fundamentals of the exponential Eq. 5 of Maillet (Dewandel et al., 2002):

$$Q_t = Q_0 \exp(-\alpha . t) \qquad (5)$$

where: Q_0 is the initial flow rate, Q_t is the flow rate at time t (daily) and α (day^{-1}) the recession coefficient characterizing the aquifer. This coefficient was obtained taking into account the base flow observed in the hydrograph recession throughout the dry period, which is better characterized between June and August (end of the hydrological year) as this period allows for characterization of the acute dry period in the region (Coelho et al., 2015a).

The recession coefficient (α) indicates the production rate of the base flow that represents the part of the streamflow which is predominately maintained by groundwater restitution (Silva et al., 2010). In this model, the decrease in the flow rate is exponential (Eq. 5), therefore, the greater α in absolute values, the closer will be the Q_t and Q_0 values, in other words, more conservation of water in the watershed with greater base flow storage, and draining supplies water more slowly into the saturated zone throughout the year providing the streamflow even during the driest periods of the year.

Having this point in mind, we understand that two hydrology year data, without gaps in the data series, can only qualitatively reflect the impacts from these two different land-uses (native forest and pasture) in the soil-water transmissivity.

The hydrology indicators considered were the ratio between base flow/runoff (BF/R) and direct surface runoff/runoff (DR/R), allowing to quantify the participation of base flow as it is a consequence of groundwater recharge, meaning it is affected by soil-water transmissivity capability of the catchment. In addition, the coefficient of depletion for both catchments were also evaluated as it allows the understanding how the saturated zone behaves in terms of drainage of water storage from the groundwater zone, being another relevant hydrogeology indicator.

3. Results and discussion

3.1 Landform characterization

Fig. 4 shows the results from the methods for landform classification proposed by Iwahashi and Pike (2007) and Geomorphons (GM) (Jasiewicz and Stepinski, 2013).

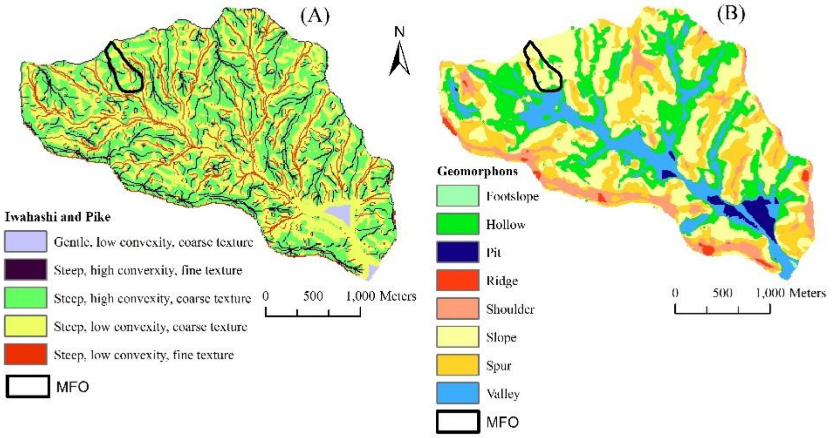

Fig. 4. Landforms according to Iwahashi and Pike (2007) (A) and Jasiewicz and Stepinski (2013) (Geomorphons) (B).

From GM only eight forms coud be recognized at LCW (Fig. 4B). It should be noted that a positive plan curvature indicates spurs and ridges, whereas, positive profile curvature typifies concave slope segments. Thus, the greatest positive values of combined curvature will characterize convex hillslopes, whereas, negative values will emphasize slope hollows such as amphitheatric valley heads (Wieczorek and Migon, 2014). Table 1 shows the spatial frequency of landforms classification methods (% of total area) for LCW.

Table 1. Spatial frequency of landforms classification methods (% Area) for LCW

Method	Landform classification	% Area
Geomorphons	Footslope	0.05
	Hollow	22.66
	Pit	1.99
	Ridge	0.78
	Shoulder	7.73
	Slope	34.17
	Spur	20.27
	Valley	12.35
Iwahashi and Pike	Steep, high convexity, fine texture	8.99
	Steep, high convexity, coarse texture	38.50
	Steep, low convexity, fine texture	9.43
	Steep, low convexity, coarse texture	42.39
	Gentle, low convexity, coarse texture	0.68

The methods of landform classification (Fig. 4) show that a background region of valleys and wetlands account for 14% of the LCW's area (GM) and about 10% of the area according Iwahashi and Pike landform classification method (Table 1). In general, the northern LCW is occupied by steep landscape and southern by a gentle landscape near to LCW's confluence (Fig. 3). The GM method (Jasiewicz and Stepinski, 2013) shows that about 34% of LCW has slope relief (Table 1) and by Iwahashi and Pike method, it was the largest landform classification (about 42% area) like steep, low convexity, coarse texture. According to CETEC (1983) and RADAMBRASIL (1983), the Mantiqueira Range region is characterized by the highest average altitudes of Minas Gerais State (from 1,100 to 2,000 m), with distinctly rugged relief, and slopes greater than 70 % and valleys extremely deep.

3.2 Validation and accuracy assessment of the predicted spatial continuity of Ksat

Table 2 shows the R^2, RMSE and MAE statistics of precision for assessment of predictive methods of spatial continuity of the Ksat at LCW.

Table 2. R^2, RMSE and MAE statistics of precision for assessment of predictive methods of spatial continuity of the Ksat at LCW

Parameters	Methods		
	TA	TA + IP	TA + GM
R^2	0.42	0.48	0.69
RMSE	1.081	1.019	0.962
MAE	0.81	0.80	0.67

According to these statistical indicators, the method that combines the terrain attributes and GM was the most efficient to predict the spatial continuity of Ksat at LCW, with greater R^2, lesser RMSE and MAE closest to 0. Since the method combining TA and GM was the most efficient, it was used to predict the spatial Ksat values for LCW.

Fig. 5 presents the Soil map (hardened) (A), solum depth map (B) (Menezes et al., 2014), Ksat maps determined by method Terrain Attributes (C), Terrain Attributes + Iwahashi and Pike (D), Terrain Attributes + Geomorphons (E) for LCW and MFO.

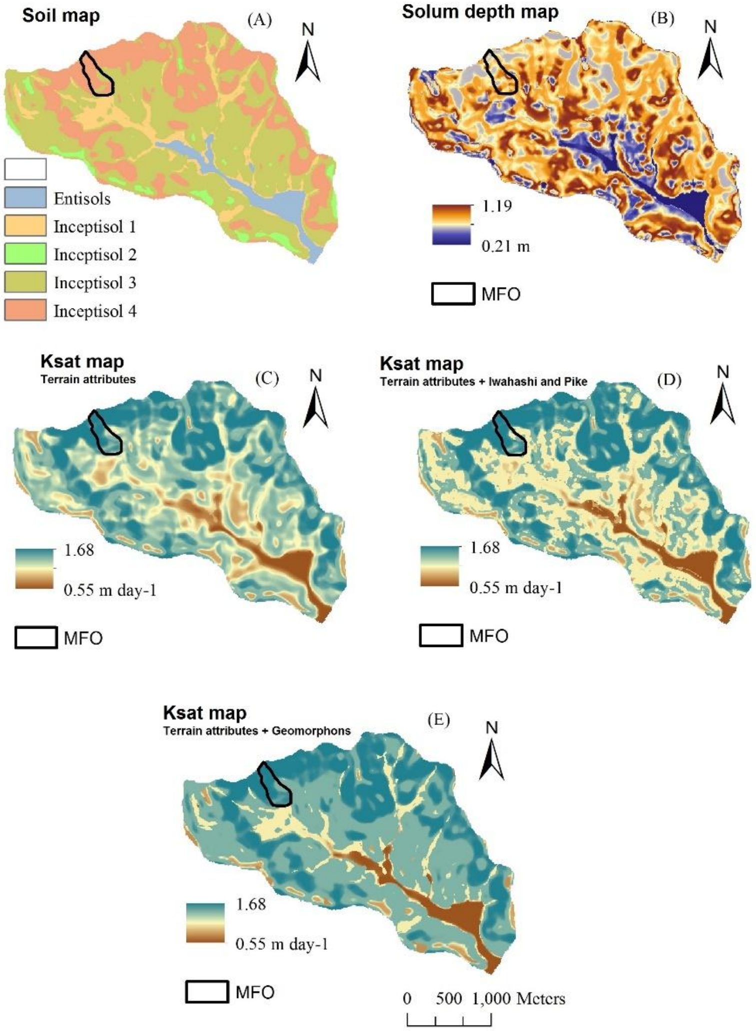

Fig. 5. Soil map (hardened) (A), solum depth map (B) (Menezes et al., 2014), Ksat maps determined by method Terrain Attributes (C), Terrain Attributes + Iwahashi and Pike (D), Terrain Attributes + Geomorphons (E) for LCW and MFO.

Since that TA + GM was the best method (Table 2) to represent the spatial distribution of Ksat for LCW, some preliminary results can be highlighted from Fig. 5E.

In the northern LCW, which is covered by native forest, the greatest Ksat values for LCW were observed as a whole. In contrast, lesser Ksat values were found in the lower areas (wetland soils) and in the slopes with a predominance of pastures in the central and southwestern portions. According to Menezes et al. (2009), this behavior can be associated with the characteristics of the Atlantic Forest in the Mantiqueira Range, having up to a 15 cm litter layer, low values of soil bulk density, high organic matter concentrations and the greatest values of drainable porosity compared to pasture, whose physiographic characteristics do not favor infiltration. According to and reported by Acreman et al. (2012), Ksat values are up to 5 times greater in the native forest conditions at the Mantiqueira Range in relation to pastures for the same soil-landscape conditions. Price et al. (2010) studying soil hydraulic properties across land uses in the southern Blue Ridge Mountains of North Carolina, USA, found Ksat values inside forests approximately seven times greater than in pastured soils. These authors stressed that the differences in soil hydraulic properties between forested and nonforested soils are due to a combination of land management and differences in macropore-forming biotic activity. In this sense, the presence of native forests in an advanced stage of development provides better conditions for the genesis of gravitational pores with high drainable porosity and soil saturated hydraulic conductivity, with formation of preferential flows throughout the soil profile (Acreman et al., 2012; Bonell et al., 2010; Hümann et al., 2011; Roa-Garcia et al., 2011).

3.3 Soil-water transmissivity map

Fig. 6 depicts the spatial distribution of soil-water transmissivity predicted using digital soil mapping techniques.

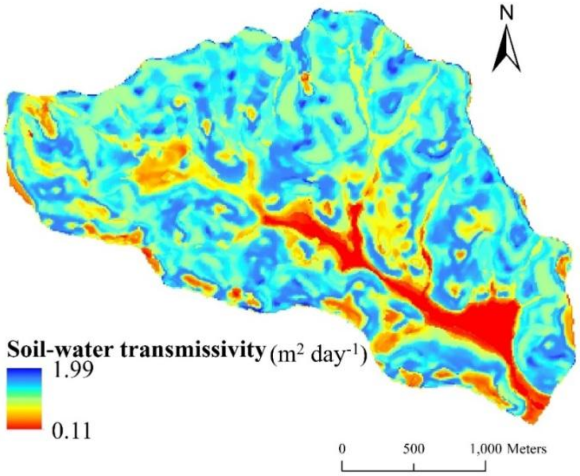

Fig. 6. Soil-water transmissivity map for LCW.

Western LCW is predominantly occupied by pasture (Fig. 1) and steepest relief (Fig. 4), and it was observed lesser values of soil-water transmissivity compared to forest (Fig. 6). Since relief and solum depth features of Inceptisols do not show optimal conditions for soil water percolation, the results showed that land-use and management are crucial for groundwater recharge in the Mantiqueira Range.

The results presented demonstrate that a relationship between areas with native forests and areas with better values of soil-water transmissivity. These results demonstrated that native forest has a strong influence on the soil-water transmissivity. Similar results were found by Soares et al. (2012) where researchers mapped soil potential infiltration in Guaratinguetá watershed, in Southeastern Brazil, in which areas with a high to moderate capacity of infiltration were found in steep hill-slopes and relatively well-preserved forest fragments.

Mello et al. (2011) evaluating the spatial distribution of top soil water content at LCW, verified that pasture sites, specifically in western LCW, presented the least values of top soil water content throughout the year. In the other words, the features of the sites occupied by low productivity pastures at LCW contribute to a significant infiltration capacity reduction, generating more substantial direct surface runoff, with soil and water losses more significant.

In order to validate the results of soil-water transmissivity, some hydrological indicators were analysed.

3.4 Hydrological background

Fig. 7 presents the observed hydrographs in both LCW and MFO sites throughout the hydrological years of 2009/2010 and 2010/2011.

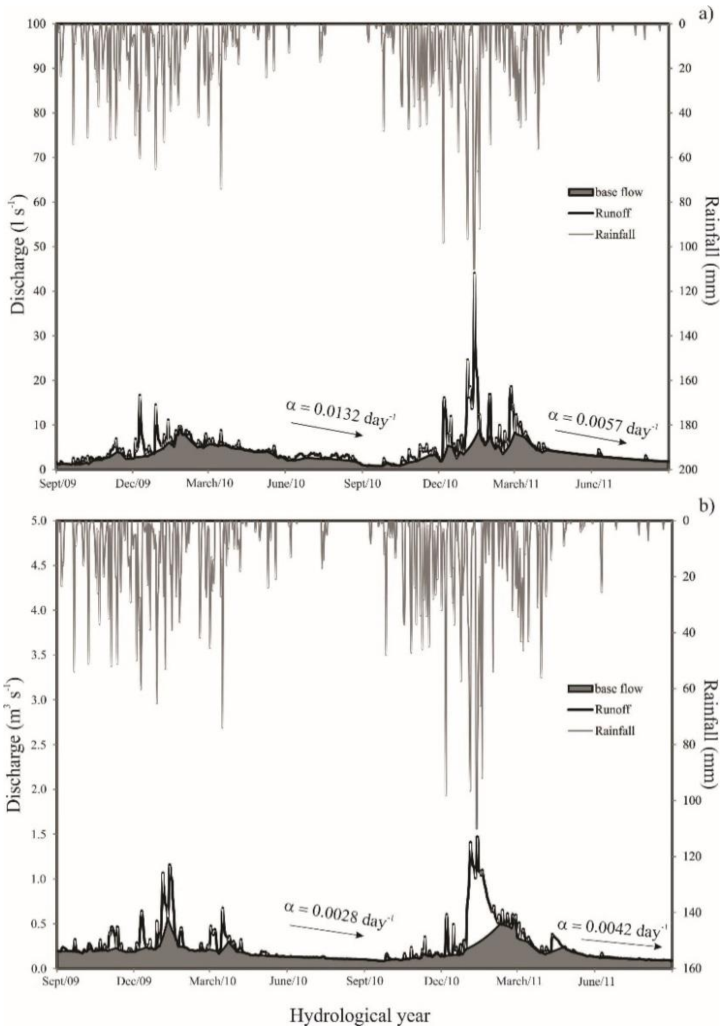

Fig. 7. Rainfall, streamflow and base flow estimated at the micro-catchment entirely occupied by native forest (MFO) (a) and Lavrinha Creek Watershed (LCW) (b) during the hydrological years of 2009/2010 and 2010/2011.

It is possible to observe intra-annual variability of the streamflow, highlitghted by the peak discharges, being a clear result of the climate characteristics of the region (high concentration of rainfall during the summer). Although the effect of the canopy of the Atlantic Forest in the rainfall intensity, for MFO, we can see greater oscillation in the hydrograph, with more frequent discharge peaks occurrence, including in the dry season as the catchment is much smaller than LCW and it has steeper relief.

It was observed that there was more concentration of rainfall in 2010-2011 hydrological year, with accentuated discharge peaks in January/2011 as a consequence of rainfall events with intensity greater than 40 mm h^{-1}, meaning more favorable conditions for occurrence of direct surface runoff at both studied sites. Although these intense rainfall events, comparing them with the average soil saturated hydraulic conductivity in MFO (64 mm h^{-1}), the direct surface runoff participation in the total runoff is less significant than the base flow. In other words, in MFO, there are more favorable conditions for infiltration of water into the soil and groundwater recharge. Thus, we can link this more significant occurrence of base flow in this catchment (in relation to LCW as a whole) to greater hydraulic conductivity of the soils under Atlantic Forest conditions.

However, considering the same above-mentioned rainfall events for January/2011, we can see that these events are much greater than the soil saturated hydraulic conductivity obtained for LCW, which is 38.51 mm h^{-1}. Under this condition, direct surface runoff had a greater addition to the total runoff in 2010-2011 hydrological year, than for MFO. In general, for both hydrological years, a greater amount of base flow could be observed in MFO, meaning there were better conditions for water infiltration and, consequently, greater water yield capacity from the groundwater system.

Table 3 presents precipitation (P), runoff (R), direct surface runoff (DR), base flow (BF) and recession coefficient (α) in the hydrological years monitored for LCW and MFO, extracted from hydrograph analyzes presented in Fig. 7.

Table 3. Hydrological indicators for the LCW and MFO

Hydrological Year	Sites	P	R	BF	DR	BF/R (%)	DR/R (%)	α (day^{-1})
		……..……(mm)……..……..						
2009/2010	LCW	2180	1250	846	404	67.7	32.3	0.0028
2010/2011		2750	1385	798	587	57.6	42.4	0.0042
2009/2010	MFO	2180	1022	785	237	76.8	23.2	0.0132
2010/2011		2750	1188	747	441	62.9	37.1	0.0057

In 2009/2010 hydrological year, the participation of the base flow to total runoff was greater for MFO, with BF/R relation of about 76.8%, which means lesser contribution of direct surface runoff to total runoff (DR/R relation of 23.2%). In LCW as a whole, these values were 67.7% and 32.3% to BF/R and DR/R, respectively, for 2009/2010 hydrological year.

This same behavior was observed for 2010/2011 hydrological year, in which base flow contribution to runoff (BF/R) in MFO was 62.9%, whereas, the contribution of direct surface runoff in the total runoff (DR/R) was 37.1%. In LCW, for the same hydrological year (2010/2011), there was values of about 57.6% and 42.4% to BF/R and DR/R respectively.

The coefficient of recession (α), in absolute values, were lesser for LCW than MFO, in both rainy seasons (0.0028 against 0.0132 and 0.0042 against 0.0057, respectively, for 2009/2010 and 2010/2011 hydrologic years).

As the decrease in flow rate is exponential (Eq. 5), the greater α in absolute values at MFO means that this area drains water stored much more slowly into the saturated zone throughout the year providing streamflow even during the driest periods of the year. Based on these coefficients, it is possible to conclude the greater ability of the groundwater system under MFO conditions to control the base streamflow.

Given that 33% of LCW's area is occupied by degraded pasture and 5% with *Eucalyptus grandis* plantation (Fig. 1), the hydrology indicators have shown that MFO has better capabilities for both storage and draining water from the shallow aquifer, contributing to maintain more significantly base flows in drier periods, and thus, generating a more stable groundwater flow system.

Price et al. (2010), in hydrological studies carried out in mountainous catchments, verified that the conversion of native to managed vegetation reduced soil infiltration and soil-water storage capabilities, resulting in increased overland flow and reduced subsurface storage. The results of Germer et al. (2010) in studies involving land-use change on near-surface hydrological processes in the Amazon basin, shows that conversion of undisturbed forest to pasture not only increased frequency and volume of stormflows, but also the contributing area and the manner in which the water moves into and through soil towards the stream channel. Pietola et al. (2005) found a significant difference in water infiltration between trampled and non-trampled soils by cattle, even though the grazing intensity had been low. Viola et al. (2013) simulated the hydrological impacts in four watersheds with similar climate and soil characteristics in the Grande River basin, and concluded that differences in runoff components within these watersheds are mainly linked to land-use differences and that the greatest contributions of surface runoff were found in watersheds with greater area occupied by agriculture and pasture. These types of land-use produce more surface runoff than forested areas because soils cultivated with crops and pasture tend to suffer more physical degradation, thus affecting their infiltration capacity.

Viola et al. (2015) assessed possible impacts in hydrology of the Upper Grande River Basin under a future climate change scenario using a hydrology model, and they verified that the dry period will tend to be more extended, being prolongated into November, by the end of this century. This result is very relevant for the Mantiqueira Range region, as it demonstrates the importance of the Atlantic Forest to be preserved at the headwaters, reducing the impacts from climate change, mainly those related to the dynamics related to groundwater recharge, affecting the base flow, and therefore, affecting the availability of water resources downstream.

The results of this study indicate a clear distinction between land-use with regard to hydropedological properties in the Mantiqueira Range region, demonstrating the role of native forests, specifically Atlantic Forest, in the behavior of water percolation in soil profile and, consequently, the water yield capacity of watersheds with well-preserved native forests. The explanations for this behavior are linked to the influence of the mature forest, highlighting: the interaction between interception and the direct impact of very intense rainfall at the surface, and soil hydrological attributes, such as saturated soil hydraulic conductivity and soil-water transmissivity. In this environment, there are conditions more favorable for the formation of more effective macropores due to the accumulation of organic matter. This finding is explicit to the Mantiqueira Range, were there is a predominance of Inceptisols and slopes greater than 20% in almost 90% of the catchment (Mello et al., 2011). The presence of native forests promote a better potential for water recharge, and mitigation of the effects associated with limited pedological and topographical factors.

Despite approximately 500 years of intense land-use changes in the Atlantic Forest, the influence of land-use changes on hydrological processes have yet to be investigated (Salemi et al., 2013). It is important to stress the lack of a hydropedological data sets for the Mantiqueira Range region, and these types of studies are increasingly needed. Our results support the idea that the consequences of the severe drought that have occurred in southeastern Brazil in 2014/2015 years, is not only due to deforestation in the Amazon region like as demonstrated by some studies (Arraut et al., 2012; Nobre, 2014), but also the deforestation of the native forests of southeastern Brazil has interfered with the production and maintenance of water supply from watersheds, therefore, decreasing ability for water recharge and natural regularization of flows in this which is the most important headwater region of Brazil.

4. Conclusions

The method combining the terrain attributes and Geomorphons was the most efficient method to predict the spatial continuity of saturated hydraulic conductivity and subsequent soil-water transmissivity in the watershed.

The Mantiqueira Range region has a considerable potential for water production and groundwater recharge, which is associated with characteristics of the Atlantic Forest in the Mantiqueira Range, where areas with high to moderate soil-water transmissivity are associated with steepest slopes, shallow Inceptisols and native forest fragments.

The soil-water transmissivity results in a micro-catchment entire covered by native forest, showed that these areas have better conditions to transmit water to the aquifer, contributing to base flow during drier periods and producing streamflows more controlled by the groundwater system.

The results showed that areas with native forests play a fundamental role in the water distribution processes in the soil profile in mountainous catchments in Southeastern Brazil. The main conclusion is that in order to protect year long flows of water to highly populated areas of Brazil, the maintenance of the remaining Atlantic Forest is imperative in these headwater areas.

5. Acknowledgments

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