UNIVERSIDADE FEDERAL DE LAVRAS

MICHELE DUARTE DE MENEZES

LEVANTAMENTO PEDOLÓGICO DE HORTOS FLORESTAIS E MAPEAMENTO DIGITAL DE ATRIBUTOS FÍSICOS DO SOLO PARA ESTUDOS HIDROLÓGICOS

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APROVADA em 16 de agosto de 2011.

Dr. João José Granate de Sá e Melo Marques	UFLA
Dr. Carlos Rogério de Mello	UFLA
Dr. Geraldo César de Oliveira	UFLA
Dr. Paulo Emílio Ferreira Motta	EMBRAPA SOLOS

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Orientador

LAVRAS – MG

2011

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RESUMO

Esta tese é composta por três capítulos, cujos estudos foram realizados em áreas localizadas em dois estados do Brasil, com diferentes finalidades. No entanto, os capítulos estão relacionados ao uso de técnicas de mapeamento digital de solos, tanto na predição de atributos físicos ou potencialidade de recarga de aquíferos, quanto no auxílio ao mapeamento de solos e manipulação de informações a partir dele. O primeiro capítulo contém um levantamento de solos em escala semidetalhada, o qual foi utilizado para o estabelecimento de unidades de manejo para o cultivo de eucalipto, no Estado do Rio Grande do Sul. As classes de solos com maior expressão geográfica foram: Argissolo Vermelho (16.900 ha), Cambissolo Háplico (9.668 ha), Argissolo Vermelho-Amarelo (7.618 ha), Argissolo Amarelo (4.289 ha). Com relação às unidades de manejo, 20% das áreas foram enquadradas como adequadas, 27% como regulares, 51% como restritas e 2% como inadequadas ao plantio de eucalipto. As principais limitações das classes de solo foram a suscetibilidade à erosão e o risco de anoxia. O segundo capítulo aborda o uso de técnicas de predição de atributos físicos do solo, comparando a acurácia da krigagem ordinária, krigagem combinada com regressão e lógicas *fuzzy*, em duas sub-bacias hidrográficas no estado de Minas Gerais. As lógicas *fuzzy*, baseadas no conhecimento das relações do solo com a paisagem e podem ser consideradas como transformações não lineares dos dados, apresentaram melhor desempenho na sub-bacia do Ribeirão Marcela (MCW), cuja variabilidade espacial segue um padrão de distribuição sistemático, devido à pedogênese. A krigagem com regressão apresentou melhor desempenho na sub-bacia do Ribeirão Lavrinha (LCW), o que sugere um maior poder de previsão desta técnica quando as formas do relevo são mais contemporâneas (predomínio de Cambissolos). O uso atual dos solos teve grande influência na variabilidade espacial dos atributos físicos. O terceiro capítulo propõe a criação de índices relacionados com a potencialidade de recarga de aquíferos, utilizando uma metodologia que integra o conhecimento do fenômeno com modelos digitais do terreno, mapas de uso atual, classes de solos e lógicas *fuzzy.* Para validação dos índices, indicadores hidrológicos foram analisados. Os índices propostos e sua predição espacial mostraram-se adequados para representar o potencial de recarga ao longo da paisagem, estando de acordo com os indicadores hidrológicos. A LCW apresentou uma maior potencialidade de recarga, devido ao papel da Mata Atlântica e maior regime de precipitação. Embora a MCW tenha melhores condições pedológicas para recarga, o uso atual e a pior distribuição de chuvas colaboraram para a menor potencialidade de recarga de aquíferos.

Palavras-chave: Mapa de solos. Manejo de solos. Geostatística. Lógicas fuzzy. Recarga de aquíferos.

ABSTRACT

This thesis consists of three chapters, whose studies were performed in two states in Brazil with different purposes. However, the chapters are related to digital soil mapping, either for prediction of physical properties, or as an auxiliary in soil mapping and manipulation of information from it. The first chapter contains a soil survey in semi-detailed scale, which was used to establish management units for eucalyptus, in the state of Rio Grande do Sul. The soil classes with largest geographical expression were Red Argisol (16.900 ha), Haplic Cambisol (9.668 ha), Red-Yellow Argisol (7.618 ha), Yellow Argisol (4.289 ha). With respect to management units, 20% of the areas were classified as adequate, 27% as regular, 51% as restricted, and 2% as inadequate for eucalyptus cultivation. The highest limitations were imposed by erosion susceptibility and oxygen deficiency. The second chapter addresses different prediction techniques of soil physical properties, comparing the accuracy of ordinary kriging, regression kriging and fuzzy logics in two watersheds in the state of Minas Gerais. The fuzzy logic, which is based on the knowledge of relationships between soil and landscape, and can be considered as a non-linear transformation of data, showed better performance in Marcela creek watershed. The spatial variability of physical properties at this watershed seems to follow a systematic pattern of distribution due to pedogenesis. The regression kriging showed better performance at LCW, what suggests higher prediction power of this technique when the landforms are more contemporary (less weathered soils). Besides the soil classes and terrain, the land use also influenced the spatial variability of physical properties. The third chapter proposes indexes related to groundwater aquifer recharge, applying a method based on knowledge of this phenomenon along with digital terrain models, land use, soil maps and fuzzy logics. Hydrologic indicators were analyzed for the validation as well as better understanding of recharge dynamic. The indexes and their continuum spatial prediction showed to be suitable for representing the potential of groundwater recharge along the landscape, and they are in agreement with hydrologic indicators. LCW showed higher potential of groundwater recharge due to the role of Atlantic Forest and larger rainfalls. Although MCW has the better pedological conditions for recharge, the land use and worse rainfalls distribution contributed for lower potential of groundwater recharge at this watershed.

Keywords: Soil map. Soil management. Geostatistics. Fuzzy logics. Groundwater recharge.

SUMÁRIO

CAPÍTULO 1

INTRODUÇÃO GERAL

Os recursos computacionais e dados tecnológicos estão amplamente difundidos e aplicados em vários ramos da ciência hoje em dia, e a Ciência do Solo não é uma exceção a essa realidade. Além disso, a melhoria constante de ferramentas como os sistemas de informações geográficas (SIGs), o uso de GPS (*global positioning system*) e modelos digitais do terreno (MCBRATNEY; SANTOS; MINASNY, 2003), constituem importantes ferramentas auxiliares ao mapeamento de solos e de seus atributos.

Nesse sentido, o levantamento de solos em áreas de plantios de eucalipto, aliado a algumas dessas ferramentas acima citadas, consistem em fundamental apoio para maior produtividade, competitividade e sustentabilidade da cultura (COSTA et al., 2009b). O levantamento de solos destaca-se também como uma base adequada, cuja indicação dos limites físicos do solo, por meio de mapas pedológicos, se apóiam em critérios que sintetizam as principais características do ambiente. Essas variáveis possuem elevado poder de síntese e capacidade preditiva (CARMO; RESENDE; SILVA, 1990).

Frente à elevada diversidade pedológica encontrada no Rio Grande do Sul (STRECK et al., 2008), e o fato da classe de solo destacar-se como estratificadora de ambientes, principalmente no âmbito dos hortos florestais (CURI, 2000), o levantamento pedológico fornece importante subsídios ao manejo silvicultural em vários aspectos (CASTRO et al., 2010; COSTA et al., 2009a; CURI, 2000; GONÇALVES, 1988; MENEZES, 2005), com destaque para o estabelecimento de unidades de manejo (COSTA et al., 2009b), cujo foco na cultura do eucalipto possibilita maior aproveitamento dos recursos disponíveis, otimização das práticas de manejo silvicultural, redução dos custos operacionais e favorecimento da sustentabilidade ambiental (NEVES, 2004). Mapas de solo apresentam adequada perfomance no fornecimento de informações, mas os resultados geralmente não refletem detalhada variabilidade espacial localmente (ZHU et al., 2010). Para isso, técnicas de geostatística que empregam krigagem ordinária, técnicas de krigagem com regressão, bem como técnicas que incorporam o conhecimento pedológico e lógicas fuzzy têm sido utilizadas para mapear atributos físico-químicos do solo bem como para mapear classes de solo (HERBST; DIEKKRÜ; VEREECKEN, 2006; MCKAY et al., 2010; ODEH; MCBRATNEY; CHITTLEBOROUGH, 1995; SUMFLETH; DUTTMANN, 2008; ZHU; BAND, 1994; ZHU et al., 1997, 2001, 2010; ZHU; LIN, 2010).

A krigagem ordinária possui como vantagem o fato de ser uma técnica considerada mais simples e pode ser performada por uma gama de softwares (HENGL; HEUVELINK; ROSSITER, 2007). Esta utiliza apenas dados observados, e nesse sentido, técnicas chamadas híbridas (combinação de técnicas para melhorar a predição espacial) têm sido preferidas (MCBRATNEY et al., 2000). Um exemplo é a krigagem aliada a regressão linear múltipla, na qual a interpolação dos dados não é baseada apenas na observação dos dados, mas também na regressão entre os atributos do solo e as variáveis do terreno e de sensoriamento remoto (HENGL; HEUVELINK; STEIN, 2004; ODEH; MCBRATNEY; CHITTLEBOROUGH, 1995). Outra abordagem que tem sido amplamente utilizada para auxiliar mapas de campo de solos e atributos são as lógicas fuzzy. Softwares que permitem a integração do conhecimento do pedólogo e esse tipo de lógica apresentam um grande potencial quanto à criação de mapas mais realísticos. E ainda, essa técnica necessita de uma menor quantidade de pontos amostrados no campo (SHI et al., 2009).

Os atributos relacionados a solos são passíveis de serem preditos usando lógicas fuzzy, vetores de similaridade (ZHU et al., 1997) e um software para a realização de inferências e para integração dos conhecimentos a respeito dos solos (SHI et al., 2009). Diversos estudos têm mostrado o êxito desta técnica na predição de atributos relacionados a solos, como por exemplo, profundidade, textura e classes de drenagem, entre outros (MCKAY et al., 2010; ZHU; BAND, 1994; ZHU et al., 1997, 2001, 2010). Com isso, por exemplo, o mapeamento da potencialidade de recarga de aquíferos de modo contínuo, utilizando esses conceitos acima, pode auxiliar no manejo do suprimento de água bem como na compreensão da dinâmica da recarga.

Desse modo, este trabalho está dividido em três capítulos, cujos objetivos foram: o levantamento pedológico em nível semidetalhado e interpretações para manejo da cultura do eucalipto no Estado do Rio Grande do Sul; a comparação da krigagem ordinária, krigagem com regressão e o uso de lógicas *fuzzy* na predição de atributos físicos do solo; e a criação de índices voltados à potencialidade de recarga de aquíferos e sua predição espacial empregando lógicas fuzzy, em duas sub-bacias hidrográficas no Estado de Minas Gerais.

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CAPÍTULO 2

Levantamento pedológico e unidades de manejo em áreas sob plantio de eucalipto no Rio Grande do Sul

RESUMO

O levantamento pedológico tem se tornado uma ferramenta importante na tomada de decisões quanto ao manejo em áreas de plantio de eucalipto, visando maior competitividade e sustentabilidade das atividades do setor. Desse modo, um levantamento pedológico semidetalhado foi realizado buscando relacionar atributos de solo e ambiente com a produtividade do eucalipto no Rio Grande do Sul. Aproximadamente 55.000 ha foram mapeados, totalizando 135 hortos florestais localizados em 29 municípios, com prospecção e amostragem, em diferentes profundidades, a cada 47 ha em média. As UMPs e suas respectivas fases de relevo foram utilizadas para o estabelecimento de unidades de manejo, criadas a partir de graus de limitação quanto à suscetibilidade à erosão (ΔE), deficiência de oxigênio (ΔO), deficiência de água (ΔH) e impedimentos a mecanização (ΔM). Os desvios foram estimados considerando-se a viabilidade de melhoramento das deficiências por meio do emprego de técnicas de manejo silvicultural de nível tecnológico mais elevado. As classes de solos com maior expressão geográfica foram: Argissolo Vermelho (16.900 ha), Cambissolo Háplico (9.668 ha), Argissolo Vermelho-Amarelo (7.618 ha), Argissolo Amarelo (4.289 ha), Neossolo Regolítico (3.505 ha), Neossolo Litólico (2.925 ha) e Planossolo Háplico (2.825 ha). Com relação às unidades de manejo, 20% das áreas de efetivo plantio foram enquadradas como adequadas, 27% como regulares, 51% como restritas, e 2% inadequadas ao plantio de eucalipto. A classe de solo e as respectivas fases de relevo destacam-se como adequadas estratificadoras de ambientes nos hortos florestais, devido à grande variabilidade pedológica e pequena variação climática nas áreas mapeadas. Quanto às classes de solo e suas limitações, destacam-se a suscetibilidade à erosão e o risco de anoxia para o cultivo do eucalipto nas áreas em questão.

Palavras-chave**:** Aptidão silvicultural. Mapeamento de solos. Ambientes de solos.

ABSTRACT

Soil survey has become an important tool in decision making in eucalyptus plantation for higher competitiveness and sustainability of the sector activities. Thereby, semi-detailed pedologic survey was done relating soil attributes and environment with eucalyptus productivity in the state of Rio Grande do Sul. Around 55.000 ha were mapped, in 135 forest gardens, in 29 counties, with prospection and sampling in different depths in each 47 ha. The UMPs and their respective relief phases were used in order to define management units created from limitation degrees related to susceptibility to erosion (ΔE), oxygen deficiency (ΔO), water deficiency (ΔH) and difficulties of mechanization (ΔM). The deviations were estimated considering the feasibility of deficiencies improvement the use of silvicultural management techniques with high technological level. The soil classes with largest geographical expression were Red Argisol (16.900 ha), Haplic Cambisol (9.668 ha), Red-Yellow Argisol (7.618 ha), Yellow Argisol (4.289 ha), Regolithic Neosol (3.505 ha), Litholic Neosol (2.925 ha), and Haplic Planosol (2.825 ha). With respect to management units, 20% of the areas were classified as adequate, 27% as regular, 51% as restricted, and 2% as inadequate for eucalyptus cultivation. The soil classes and their respective relief phases stood out as appropriate stratifiers of environments in forest gardens due to larger pedologic variability and lower climatic variability in the areas mapped. The highest limitations were imposed by erosion susceptibility and oxygen deficiency.

Keywords: Silvicultural suitability. Soil mapping. Soil environments.

1 INTRODUÇÃO

A cultura do eucalipto é um vetor no desenvolvimento socioeconômico no cenário atual brasileiro, sendo responsável por significativa parcela no PIB nacional e na geração de empregos (ASSOCIAÇÃO BRASILEIRA DA INDÚSTRIA DE MADEIRA PROCESSADA MECANICAMENTE - ABIMCI, 2011), com áreas de plantio em acelerado ritmo de expansão (ASSOCIAÇÃO BRASILEIRA DE PRODUTORES DE FLORESTAS PLANTADAS - ABRAF, 2011). Para a manutenção da competitividade do setor, o levantamento pedológico e sua interpretação têm se revelado apoios importantes na tomada de decisões em áreas de plantação de eucalipto.

Frente à diversidade pedológica encontrada nas áreas mapeadas (STRECK et al., 2008), a classe de solo destaca-se como estratificadora de ambientes, principalmente no âmbito do horto florestal (CURI, 2000). Por meio dos levantamentos de solos são identificadas e mapeadas as diversas classes existentes em uma determinada área, diferenciadas pelas características morfológicas, físicas, químicas e mineralógicas, que têm se mostrado fundamentais para a utilização adequada desse recurso natural (MOTTA et al., 2001). Tanto a classificação taxonômica de solos quanto a indicação de seus limites físicos, por meio de mapas pedológicos, se apoiam em critérios que sintetizam as principais características ambientais, variáveis de elevado poder de síntese e capacidade preditiva (CARMO; RESENDE; SILVA, 1990), desde que em escala adequada para não acarretar em interpretações incorretas (COSTA et al., 2009b).

Assim, o levantamento pedológico, com seu relevante papel de estratificar ambientes, fornece subsídios à cultura do eucalipto quanto aos seguintes aspectos: na determinação de unidades de manejo apoiadas nas principais limitações dos solos (COSTA et al., 2009c); determinação de áreas com risco de anoxia mediante a sensibilidade da cultura à deficiência de O_2 (CASTRO et al., 2010; COSTA et al., 2009a; CURI, 2000); apoio em estudos de produtividade da cultura (CASTRO et al., 2010; MENEZES, 2005); subsídios ao inventário florestal, refletindo uma adequada produção total de um talhão, quando este for heterogêneo (MENEZES, 2005); seleção de clones para plantio; extrapolação de resultados experimentais; predição de crescimento e da qualidade da madeira; interpretação da resposta à fertilização e técnicas silviculturais (GONÇALVES, 1988); e apoio nos processos de certificação ambiental. Dentre estes, destaca-se o estabelecimento das unidades de manejo, cujo foco na cultura do eucalipto possibilita maior aproveitamento dos recursos disponíveis, otimização das práticas de manejo silvicultural, redução dos custos operacionais e favorecimento da sustentabilidade ambiental (NEVES, 2004).

Deste modo, este trabalho teve como objetivos a utilização do levantamento pedológico e suas interpretações para o estabelecimento de unidades de manejo em áreas de plantio de eucalipto, no Estado do Rio Grande do Sul.

2 MATERIAL E MÉTODOS

2.1 Descrição geral das áreas mapeadas

Os hortos florestais estudados situam-se entre as coordenadas 51°24’13.8” e 54°47’30.9” de longitude oeste, e as coordenadas 29°46’38.9” e 31°9’37.2” de latitude sul no estado do Rio Grande do Sul, localizados nos municípios de Arroio dos Ratos, Barão do Triunfo, Barra do Ribeiro, Butiá, Caçapava do Sul, Cachoeira do Sul, Camaquã, Canguçu, Cerro Grande do Sul, Cristal, Dom Feliciano, Eldorado do Sul, Encruzilhada do Sul, Guaíba, Lavras do Sul, Mariana Pimentel, Minas do Leão, Pantâno Grande, Rio Pardo, Rosário do Sul, Santa Margarida do Sul, Santa Maria, São Gabriel, São Jerônimo, São Lourenço do Sul, São Sepé, Tapes, Triunfo e Vila Nova do Sul. Os hortos florestais estão representados na Figura 1. Na Figura 2 são apresentados os mapas das unidades geomorfológicas (a) e unidades fisiográficas (b).

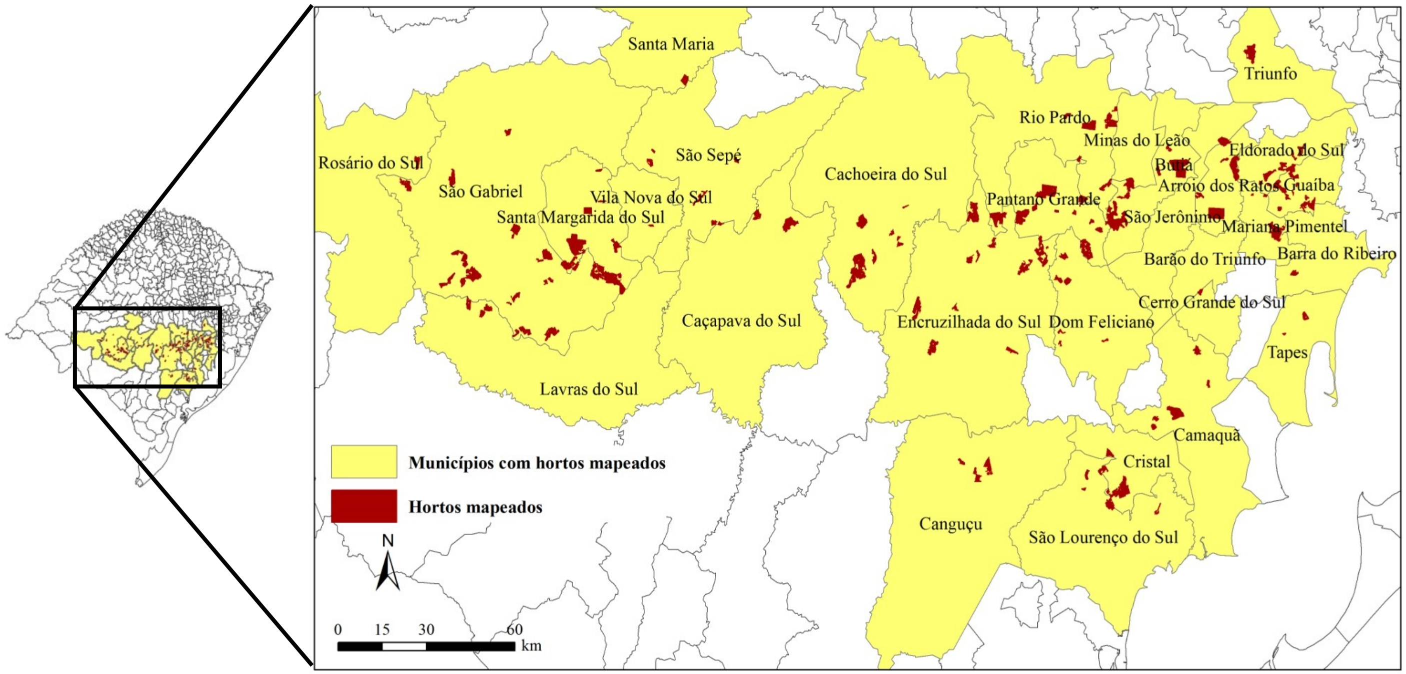

Figura 1 Municípios e hortos florestais mapeados

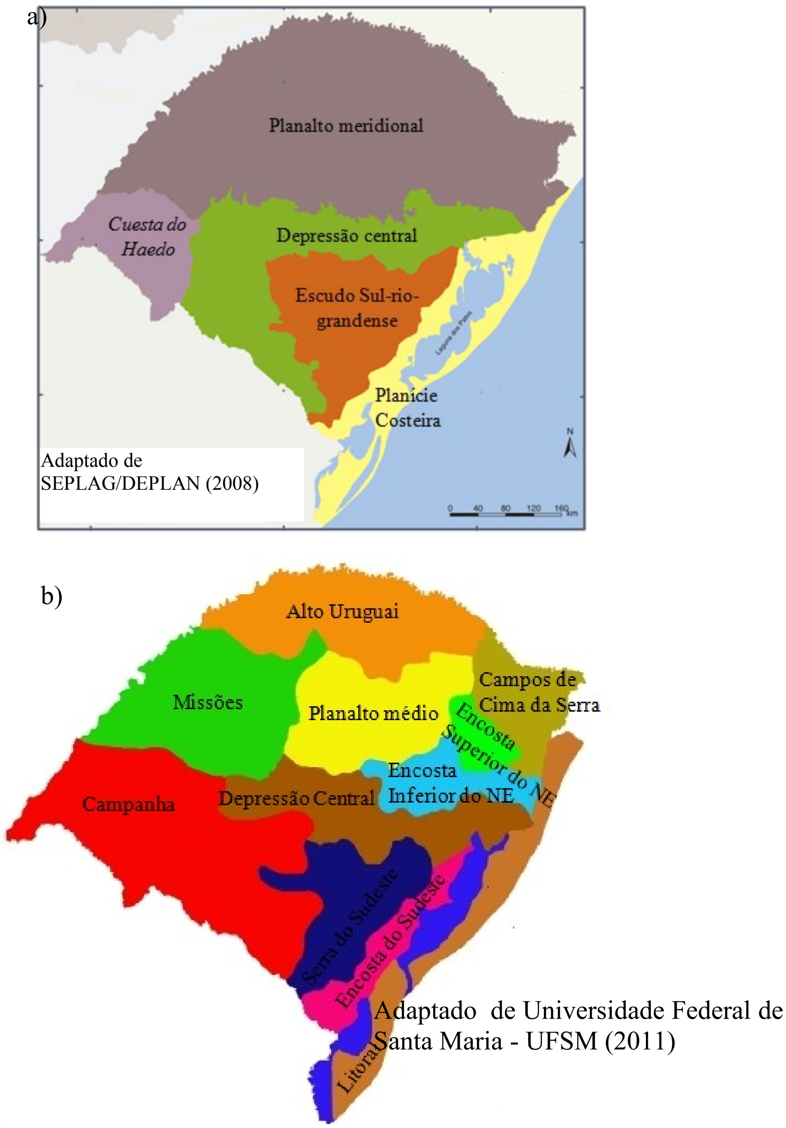

Figura 2 Unidades geomorfológicas (a) e regiões fisiográficas (b) do Estado do Rio Grande do Sul

A vegetação nativa é composta por mata subtropical alta e mata subtropical arbustiva. O clima predominante, segundo a classificação de Köppen, é o Cfa, subtropical (ou virginiano) úmido sem estiagem, cuja temperatura do mês mais quente é superior a 22ºC e a do mês mais frio varia de 3 a 18ºC. As chuvas ocorrem bem distribuídas durante todos os meses do ano, sendo que a amplitude de variação entre os meses de máxima e mínima precipitação não chega a ser significativa para caracterizar o clima como tendo um período chuvoso e outro seco (CASTRO et al., 2010).

As áreas estudadas pertencem a três regiões geomorfológicas distintas (Figura 2a): Escudo Sul-Rio-Grandense, Depressão Central Gaúcha e Planície Costeira (RIO GRANDE DO SUL, 2008). A maior parte das áreas mapeadas encontra-se no Escudo Sul-rio-grandense, de geologia complexa e com as rochas mais antigas presentes no Estado. A litologia é composta predominantemente por granitos e gnaisses do Proterozóico (2300 Ma), recobertas por sedimentos do Paleozóico (465 Ma) (RAMGRAB et al., 2004). A Depressão Central Gaúcha consiste em uma sucessão complexa de diferentes tipos de rochas sedimentares que circunda o Escudo Sul-Rio-Grandense. Nas cotas mais baixas encontra-se a Planície Costeira, formada por sedimentos inconsolidados (areias, siltes e argilas) depositados a partir do período Terciário (65 – 2 Ma) e durante o Quaternário (2 Ma) (STRECK et al., 2008). Já as regiões fisiográficas (Figura 2b) onde se localizam os hortos florestais são: Depressão Central, Serra do Sudeste, Encosta do Sudeste e Encosta Inferior do Nordeste (BRASIL, 1973).

2.2 Métodos de trabalho de campo e escritório

O levantamento pedológico foi realizado para possibilitar o estabelecimento de relações entre os atributos de solo e ambiente com a produtividade do eucalipto. Minitrincheiras foram abertas e amostras foram coletadas nas profundidades de 0-20, 40-70 e 100-120 cm, quando não havia impedimento físico. Perfis modais foram descritos e amostrados. O método de prospecção utilizado foi do tipo caminhamento livre, percorrendo toda a área e realizando observações de campo e coletas de amostras sempre que havia indicação mudanças de classes dos solos e/ou de atributos relevantes para a cultura do eucalipto. A descrição dos perfis modais e das minitrincheiras, além da coleta de amostras, foram realizadas de acordo com os procedimentos normatizados por Lemos et al. (2005) e os solos foram classificados de acordo com a Empresa Brasileira de Pesquisa Agropecuária - EMBRAPA (2006). Análises físicas e químicas foram realizadas de acordo com EMBRAPA (1997).

Todas as minitrincheiras e perfis modais observados e coletados em campo foram georreferenciados com GPS (*global positioning system*). Os mapas de solos foram confeccionados em ambiente de sistema de informações geográficas (SIG) utilizando o software ArcGIS 9.3 da ESRI. O critério fase de relevo foi criado a partir da combinação entre mapas de solos e mapas de declividade. Estes últimos foram calculados a partir de modelo digital de elevação, gerado a partir de curvas de nível com equidistância de 5 m a partir de malha triangular (TIN). Classes de relevo foram adaptadas de Lemos et al. (2005).

2.3 Critérios adotados para estabelecimento das Unidades de Mapeamento Pedológicas (UMPs)

Foi criada uma legenda que contém a relação completa das UMPs identificadas e delineadas nas áreas estudadas, baseada no Sistema Brasileiro de Classificação de Solos (SiBCS) da EMBRAPA (2006) e Lemos et al. (2005). A legenda é adaptada às condições da cultura do eucalipto para as regiões fisiográficas estudadas. Abaixo encontram-se maiores detalhes sobre os critérios adotados para o estabelecimento das UMPs bem como das fases de relevo.

a) atividade da argila e saturação de bases:

- atividade alta (Ta) consiste em valores superiores a 27 $cmol_c$/kg de argila e atividade baixa corresponde a valores inferiores a 27 $cmol_c$/kg de argila (Tb), e quanto à saturação por bases (V>50% - eutrófico; V<50% - distrófico);

b) grupamento generalizado de classes de textura e quantidade de cascalho:

- as classes de textura generalizadas e acompanhadas da presença ou não de cascalhos, são representadas como: a – textura arenosa; m – textura média; r – textura argilosa; c – presença de cascalhos;

c) tipos de horizonte A:

- os solos com horizonte A fraco foram separados dos demais (chernozêmico, húmico, proeminente e moderado), servindo como critério para auxiliar na distinção das UMPs;

d) profundidade efetiva:

- as classes de profundidade do *sólum* consideradas nesse estudo foram: rasos (≤ 50 cm de profundidade), pouco profundos (>50 e ≤100 cm de profundidade) e profundos (> 100 e ≤ 200 cm de profundidade);

e) classes de drenagem:

- nos solos excessivamente drenados, a água é removida rapidamente, o que é comum em solos de elevada porosidade, ou no caso deste estudo, em solos com textura arenosa. Já nos acentuadamente drenados, a água também é removida rapidamente do perfil, no entanto, pertencem a esta classe solos de textura argilosa e média, muito porosos e permeáveis, como é o caso dos Latossolos. A água é removida rapidamente no perfil dos solos bem drenados, apresentando textura argilosa ou média, sem presença de mosqueados até a profundidade coletada (máximo 120 cm). A classe de drenagem moderadamente drenada contempla solos que possuem uma camada de permeabilidade lenta no *sólum* ou abaixo dele, onde a água é removida do solo um tanto quanto lentamente, de modo que o perfil permanece molhado por uma pequena parte do tempo; apresentam alguns mosqueados na parte inferior ou no topo do B. As classes bem drenados e moderadamente drenados são as mais frequentes dentre os solos estudados. As classes de drenagem excessicamente, bem e moderadamente drenados, embora se refiram a solos com boa porosidade, a distinção entre eles é feita basicamente em função da retenção de água. Os imperfeitamente drenados apresentam mosqueados e indícios de gleização na parte baixa do perfil, pois a água é removida do solo lentamente, permanecendo úmido por período significativo, mas não durante a maior parte do ano. Já nos mal drenados, a água é removida do perfil lentamente, deixando-os úmidos em grande parte do ano. Apresentam mosqueados e características de gleização, e nesse levantamento de solos incluem os Planossolos Háplicos gleissólicos e os Gleissolos Háplicos. Solos onde o lençol freático permanece à superfície durante a maior parte do ano são enquadrados como muito mal drenados, como os Gleissolos Melânicos. Os solos considerados como bem drenados também incluem aqueles excessivamente/bem drenados. Os moderadamente drenados incluem aqueles excessivamente/moderadamente drenados e os imperfeitamente drenados incluem aqueles excessivamente/imperfeitamente drenados;

f) pedregosidade:

- solos pedregosos contém calhaus e/ou matacões ocupando 1 a 3% da massa do solo e/ou da superfície do terreno (distanciando-se de 1,5 a 10 m), tornando difícil o uso de maquinário agrícola convencional, podendo, entretanto, os solos serem utilizados para plantios florestais, se outras características forem favoráveis. Solos epipedregosos contêm calhaus e/ou matacões na parte superficial e/ou dentro do solo até a profundidade máxima de 40 cm; já os endopedregosos contém calhaus e/ou matacões concentrados em profundidades maiores que 40 cm;

g) rochosidade:

- nos solos rochosos, os afloramentos são suficientes para restringir cultivos entre as rochas ou matacões, o que ainda permite o plantio florestal. Os afloramentos e matacões se distanciam de 10 a 30 m, ocupando de 10 a 25% da superfície do terreno;

h) fases de relevo:

- declives de 0-8% foram enquadrados como planos e suave ondulados, 8-20% como ondulados e 20-75% como forte ondulados e montanhosos.

2.4 Critérios adotados para estabelecimento de unidades de manejo

As unidades de mapeamento pedológicas (UMPs) foram constituídas a partir de dados obtidos do levantamento pedológico semidetalhado e da paisagem. Essas informações, aliadas a dados de produtividade e à experiência acumulada de técnicos que atuam nas regiões estudadas, com base nos conceitos de Ramalho Filho e Beek (1995), foram utilizadas para a determinação dos graus de limitações (desvios) dos parâmetros do solo e ambiente que refletem no desenvolvimento do eucalipto: suscetibilidade à erosão (ΔE), deficiência de oxigênio (ΔO), deficiência de água (ΔH) e impedimentos ao manejo (ΔM). Os desvios foram estimados considerando-se a viabilidade de melhoramento das deficiências por meio do emprego de técnicas de manejo silvicultural de nível tecnológico mais elevado.

Os graus de limitação ligados à suscetibilidade à erosão (ΔE) são comandados pelas fases de relevo, seguidos da profundidade efetiva e textura. A suscetibilidade à erosão aumenta com o aumento da declividade, com a diminuição da profundidade efetiva (maior suscetibilidade à erosão em solos horizonte B, como os Neossolos Litólicos e Regolíticos, com horizonte Bi, com horizonte plíntico ou outros tipos de horizonte B, porém rasos), e com o aumento no teor de areia, como no caso dos solos arênicos ou Neossolo Quartzarênico. Solos em relevo forte ondulado e montanhoso, independente da profundidade efetiva e textura, apresentam grau de limitação forte. Os graus de limitação ou desvios são apresentados na Tabela 1.

Tabela 1 Critérios para definição do grau de limitação por suscetibilidade à erosão (ΔE) para a cultura do eucalipto no Rio Grande do Sul

Graus de limitação	**Fases de relevo**[1]	**Profundidade efetiva**[2]	**Textura**
Nulo	P_so; plano de várzea	Profundos e pouco profundos (Argissolos, Nitossolos, Planossolos)	Qualquer, exceto caráter arênico ou textura arenosa em todo o perfil
Ligeiro	P_so	Solos sem horizonte B, horizonte plíntico, Cambissolos ou rasos	Qualquer, exceto caráter arênico ou textura arenosa em todo o perfil
	P_so	Solos profundos e pouco profundos (Argissolos, Nitossolos, Planossolos)	Qualquer, exceto caráter arênico ou textura arenosa em todo o perfil
Moderado	P_so; O	Solos sem horizonte B, Cambissolos, rasos, pouco profundos e profundos	Arênicos ou arenosos em todo o perfil
	O	Solos sem horizonte B, horizonte plíntico, Cambissolos ou rasos	Qualquer, desde que solo não tenha caráter arênico textura arenosa em todo o perfil
Forte	Fo_m	Qualquer profundidade	Qualquer textura

[1]Fases de relevo: P_so – plano, suave ondulado; O – ondulado; Fo_m: forte ondulado, montanhoso. [2]Bt – horizonte B textural

Os critérios considerados quanto aos graus de limitação por deficiência de oxigênio (ΔO) consistem na integração entre as classes de drenagem, fases de relevo e profundidade efetiva e/ou classes de solos (Tabela 2). Este último resultou da combinação de dois critérios para melhor distinguir os solos e suas limitações, como os Neossolos Regolíticos, que são moderadamente profundos, porém foram agrupados juntamente com os solos rasos ou plínticos. O mesmo critério foi considerado para solos com horizonte plíntico, que apresentam diferentes profundidades, no entanto, estes solos são formados sob condições de restrição à percolação da água, que tem como consequência a formação do horizonte plíntico (EMBRAPA, 2006).

Tabela 2 Critérios para definição do grau de limitação por deficiência de oxigênio (ΔO) para a cultura do eucalipto no Rio Grande do Sul

Graus de limitação	**Drenagem**	**Fase de relevo**[1]	**Profundidade efetiva/classe de solo**
Nulo	Bem drenado ou moderadamente drenado	Qualquer	Pouco profundo ou profundo
	Excessivamente, acentuadamente drenados	Qualquer	Qualquer
Ligeiro	Imperfeitamente drenado	O, fo_m	Pouco profundo ou profundo
	Bem drenado, moderadamente drenado	O, fo_m	Raso, Neossolo Regolítico, plínticos
Moderado	Imperfeitamente drenado	P_so	Pouco profundo ou profundo
	Bem drenado, moderadamente drenado	P_so	Raso, Neossolo Regolítico, plínticos
Forte	Mal ou muito mal drenado	P_so, plano de várzea	Qualquer

[1]Fases de relevo: P_so – plano, suave ondulado; O – ondulado; Fo_m: forte ondulado, montanhoso

Os critérios adotados para definição dos graus de limitação por deficiência de água (ΔA) foram: classes de drenagem, profundidade efetiva e/ou classes de solo e fases de relevo (Tabela 3). Solos rasos, mesmo em relevo plano/suave ondulado, possuem baixo volume de armazenamento de água. Considerando a deficiência de oxigênio, pequena profundidade em relevo plano/suave ondulado implica em maior risco de anoxia às plantas de eucalipto.

Tabela 3 Critérios para definição do grau de limitação por deficiência de água (ΔA) para a cultura do eucalipto no Rio Grande do Sul

Graus de limitação	**Drenagem**	**Fase de relevo[1]**	**Profundidade efetiva/classe de solo**
Nulo	Mal e muito mal drenado	Qualquer	Qualquer
Nulo/Ligeiro	Imperfeitamente drenado	P_so	Profundo, moderadamente
Ligeiro	Acentuadamente, bem e moderadamente drenado	Qualquer	Profundo, moderadamente
	Imperfeitamente drenado	O, Fo_m	Profundo e moderadamente profundo
Moderado	Bem e moderadamente drenado	P_so	Raso, Neossolo Regolítico, plíntico
Forte	Excessivamente drenados, arênicos	Qualquer	Qualquer
	Bem e moderadamente drenado	O, Fo_m	Raso, Neossolo Regolítico, plíntico

[1]Fases de relevo: P_so – plano, suave ondulado; O – ondulado; Fo_m: forte ondulado, montanhoso

Quanto aos critérios considerados para os graus de limitação por impedimentos ao manejo utilizou-se a profundidade efetiva e/ou classe de solo (tipo de horizonte B, ou falta desse, e profundidade), fase de relevo, classes de drenagem e outras limitações, que estão relacionadas principalmente ao adensamento e rochosidade.

Tabela 4 Critérios para definição do grau de limitação por impedimentos a mecanização (ΔM) para a cultura do eucalipto no Rio Grande do Sul

Graus de limitação	Classe de solo/profundidade	Relevo[1]	Drenagem	Outras limitações
Nulo	RQ, arênicos, Bw	P_so; o	Excessivamente, acentuadamente drenados	-
Ligeiro	Profundos com horizonte Bt, Bn	P_so; o	Bem drenados	-
	RQ, arênicos, Bw	Fo_m	Excessivamente, acentuadamente	-
Ligeiro/moderado	Sem B, Bi, rasos	P_so; o	Bem drenados	-
Moderado	Quaisquer	P_so; o	Imperfeitamente drenados	-
		P_so; o	Bem, moderadamente drenados	Adensado
		P_so; o	Bem, moderadamente drenados	Rochoso
Moderado/forte	Quaisquer	P_so; o	Imperfeitamente drenados	Adensado
		P_so; o	Imperfeitamente drenados	Rochoso
Forte	Quaisquer, exceto RQ, solos com Bw, ou arênicos	Plano de várzea	Mal, muito mal drenados	-
		Fo_ m	Bem, moderado, imperfeitamente drenados	-

[1]Fases de relevo: P_so – plano, suave ondulado; O – ondulado; Fo_m: forte ondulado, montanhoso

De posse dos desvios ΔE, ΔA, ΔO, e ΔM, um quadro guia foi elaborado para o estabelecimento das unidades de manejo para a cultura do eucalipto para no Rio Grande do Sul, o que indica qual fator ou fatores limitantes impõem maores restrições ao manejo silvicultural. As classes de unidades de manejo adequadas, regulares, restritas e inadequadas foram identificadas (Tabela 5), onde o grau de limitação colocado consiste no mais restritivo.

Tabela 5 Quadro guia de enquadramento das unidades de manejo para o cultivo do eucalipto no Rio Grande do Sul

ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
Nulo	Ligeiro	Ligeiro	Ligeiro	Adequado
Ligeiro	Moderado	Ligeiro	Ligeiro/moderado	Regular
Moderado-Forte	Forte	Moderado	Moderado-Forte	Restrito
-	-	Forte	-	Inadequado

ΔE: suscetibilidade à erosão; ΔA: deficiência de água; ΔO: deficiência de oxigênio; ΔM: impedimentos a mecanização

3 RESULTADOS E DISCUSSÃO

3.1 Hortos florestais mapeados em nível de semidetalhe

As áreas mapeadas totalizam uma extensão de aproximadamente 55.000 ha de áreas destinadas ao plantio (não se incluem aqui áreas de preservação permanentes e nem afloramentos de rochas), totalizando 135 hortos florestais mapeados. Foram realizadas 1157 prospecções de campo, com densidade de amostragem de 0,02 observações/ha, com uma média de um local descrito e amostrado, em diferentes profundidades, a cada 47 ha. Abaixo se encontra a legenda que contempla as UMPs. Com relação as texturas, as seguintes siglas significam: a – arenosa, m – média e r – argilosa.

PAC – Argissolo Acinzentado Plíntico, Típico, Raso, textura m/m/m; m/m/r; m/r/r; r/r/r, m/r, A moderado, húmico, profundo, raso, Tb-Ta, distrófico.

PA1 – Argissolo Amarelo Arênico, textura a/a/r, a/a/m, A moderado, profundo, excessivamente/moderadamente drenado, Tb-Ta, distrófico.

PA2 – Argissolo Amarelo Arênico, textura a/a/m, A moderado, profundo, excessivamente/imperfeitamente drenado, Ta, distrófico.

PA3 - Argissolo Amarelo Arênico, Epiáquico, textura a/a/m, A moderado, profundo, excessivamente/moderadamente drenado, Tb, distrófico.

PA4 – Argissolo Amarelo Gleissólico, textura m/r/r, m/m/r, A fraco, profundo, imperfeitamente drenado, Tb, distrófico.

PA5 - Argissolo Amarelo Epiáquico, Gleissólico, Raso, textura m/r/r, m/m/r, m/m/m, r/r/r, a/m/r, m/r, mc/rc, A proeminente, húmico, moderado, profundo, raso, imperfeitamente; excessivamente/imperfeitamente drenado, Tb-Ta, distrófico.

PA6 – Argissolo Amarelo Raso, textura m/r, m/rc, r/m, m/m, A proeminente, moderado, pedregoso, ausente, moderadamente drenado, Tb-Ta, distrófico.

PA7 – Argissolo Amarelo Típico, textura m/r/r, m/rc/rc, mc/ac/rc, m/a/m, A fraco, profundo, moderadamente drenado, Tb, distrófico.

PA8 – Argissolo Amarelo Típico, textura m/m/r, m/r/r, A fraco, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PA9 – Argissolo Amarelo Típico, textura m/r, m/mc/rc, A fraco, epipedregoso, pouco profundo, profundo, moderadamente drenado, Tb-Ta, distrófico.

PA10 – Argissolo Amarelo Típico, textura ac/mc/mc, A moderado, pedregoso, pouco profundo, excessivamente/moderadamente drenado, Tb, distrófico

PA11 – Argissolo Amarelo Típico, textura m/m/r, m/mc/rc, m/r/r, m/r/m, m/a/m, m/m/m, mc/mc/mc, m/rc/rc, mc/r/r, mc/rc/rc, a/m/m, A húmico, proeminente, moderado, pouco profundo, profundo, moderadamente, excessivamente/moderadamente drenado, Tb-Ta, distrófico.

PA12 - Argissolo Amarelo Típico, textura m/m/r, m/r/r, m/m/m, mc/r/r, m/r, r/mc/r, A húmico, proeminente, moderado, pouco profundo, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PA13 - Argissolo Amarelo Plíntico/Adensado, textura m/r/m, A fraco, pouco profundo, moderadamente drenado, Ta, distrófico.

PA14 - Argissolo Amarelo Adensado, textura m/r, A moderado, profundo, moderadamente drenado, Ta, distrófico.

PA15 - Argissolo Amarelo Gleissólico, textura m/mc/rc, A proeminente, epipedregoso, profundo, imperfeitamente drenado, Ta-Tb, distrófico-eutrófico.

PV1 - Argissolo Vermelho Arênico, textura a/a/r, A fraco, profundo, excessivamente-bem drenado, Tb, distrófico.

PV2 - Argissolo Vermelho Adensado, textura m/r/r, a/r/r, mc/r, mc/rc, m/r, A fraco, pouco profundo, profundo, excessivamente/moderadamente-bem drenado, Tb-Ta, distrófico.

PV3 - Argissolo Vermelho Adensado, textura m/r/r, mc/r/r, r/rc, m/mc, mc/mc, mc/rc, mc/rc/rc, A moderado, pouco profundo, profundo, bem drenado, Tb-Ta, distrófico.

PV4 – Argissolo Vermelho Adensado, textura m/r, A moderado, epipedregoso-endopedregoso, profundo, moderadamente e bem drenado, Tb-Ta, distrófico.

PV5 - Argissolo Vermelho Adensado, Raso, textura m/r, A fraco, bem drenado, Tb, distrófico.

PV6 – Argissolo Vermelho Adensado, Raso, textura m/r, A fraco, pedregoso, moderadamente drenado, Tb, distrófico.

PV7 - Argissolo Vermelho Epiáquico, Gleissólico, textura m/r/r, mc/r/r, m/mc/mc, A moderado, proeminente, pouco profundo, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PV8 - Argissolo Vermelho Raso, textura m/r, m/rc, mc/r, mc/rc, m/rc/rc, A fraco, bem drenado, Tb, distrófico.

PV9 - Argissolo Vermelho Raso, textura mc/rc, mc/r, A fraco, pedregoso, bem drenado, Ta, distrófico.

PV10 – Argissolo Vermelho Raso, textura m/r, m/rc, mc/r, mc/rc, a/m, A húmico, moderado, bem, excessivamente/bem drenado, Tb, distrófico.

PV11 - Argissolo Vermelho Raso, textura mc/rc, A moderado, pedregoso, bem drenado, Ta, distrófico.

PV12 - Argissolo Vermelho Típico, textura a/m/r, m/r/r, m/rc/rc, mc/r/r, a/mc/r, mc/mc/mc, mc/rc/rc, a/rc/rc, m/m/r, rc/r/r, m/m/m, r/r/r, m/rc/r, A fraco, pouco profundo, profundo, excessivamente/bem-moderadamente drenado, Ta-Tb, distrófico-eutrófico.

PV13 - Argissolo Vermelho Típico, textura m/r/r , m/rc/rc, r/r/r, A fraco, epipedregoso-endopedregoso-pedregoso, pouco profundo, bem-moderadamente drenado, Ta-Tb, distrófico.

PV14 - Argissolo Vermelho Típico, textura m/m/m, mc/mc/mc, m/m/r, m/mc/rc, mc/mc/rc, m/r/m, m/r/r, m/rc/r, m/rc/rc, mc/r/r, mc/rc/rc, r/r/r, r/rc/r, rc/r/r; m/a/r, m/ac/rc, m/mc/r, a/m/r, ac/rc/m; a/m/m; a/r/r, rc/rc/rc, m/rc/mc, m/m/rc, m/rc, m/r, r/rc, s/r/r, A húmico, proeminente, moderado, pouco profundo, profundo, bem-moderadamente-excessivamente/bem drenado, Tb-Ta, distrófico-eutrófico.

PV15 – Argissolo Vermelho Típico, textura m/r/r, m/rc/m, A húmico, moderado, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PV16 - Argissolo Vermelho Típico, textura a/m/r, ac/m/r, ac/r/r, m/m/r, m/r/r, mc/r/r, mc/rc/rc, mc/m/r, m/r, m/r/m, m/rc/rc, A proeminente, moderado, epipedregoso-endopedregoso-pedregoso, pouco profundo, profundo, moderadamente-bem-excessivamente/bem drenado, Tb-Ta, distrófico.

PV17 - Argissolo Vermelho Petroplíntico, textura m casc/r; m casc/r/r, m/a/r, A Moderado, epipedregoso-endopedregoso, pouco profundo, profundo, bem drenado, Tb-Ta, distrófico.

PV18 - Argissolo Vermelho Arênico, textura a/a/r, a/a/m, A moderado, profundo, excessivamente/bem drenado, Tb-Ta, distrófico-eutrófico.

PV19 - Argissolo Vermelho Típico, textura mc/rc/rc, A moderado, rochoso, pouco profundo, bem drenado, Tb-Ta, distrófico-eutrófico.

PVA1 - Argissolo Vermelho-Amarelo Adensado, textura m/r/r, mc/rc, m/m/r, m/r, A fraco, pouco profundo, profundo, bem drenado, Tb, distrófico.

PVA2 - Argissolo Vermelho-Amarelo Adensado, textura m/r/r, m/m/r, m/r, A húmico, moderado, pouco profundo, profundo, bem drenado, Tb-Ta, distrófico.

PVA3 - Argissolo Vermelho-Amarelo Arênico, textura a/a/m, A fraco, profundo, excessivamente/bem drenado, Ta, distrófico.

PVA4 - Argissolo Vermelho-Amarelo Arênico, textura a/a/m, A fraco, rochoso, pouco profundo, excessivamente/bem drenado, Tb, distrófico.

PVA5 - Argissolo Vermelho-Amarelo Arênico, textura a/a/m, A fraco, pedregoso, pouco profundo, excessivamente/bem drenado, Ta, distrófico.

PVA6 - Argissolo Vermelho-Amarelo Arênico, textura a/a/m, a/a/mc, ac/ac/mc, A moderado, pouco profundo, profundo, excessivamente/bem drenado, Tb-Ta, distrófico.

PVA7 - Argissolo Vermelho-Amarelo Epiáquico, Gleissólico, Plíntico, textura m/m/r, m/r/r, r/r/r, A chernozêmico, húmico, proeminente, moderado, pouco profundo, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PVA8 – Argissolo Vermelho-Amarelo Gleissólico, textura mc/r/r, A fraco, epipedregoso, profundo, moderadamente drenado, Ta, distrófico.

PVA9 – Argissolo Vermelho-Amarelo Raso, textura mc/r, A fraco, epipedregoso-endopedrego, moderadamente drenado, Tb, distrófico.

PVA10 - Argissolo Vermelho-Amarelo Raso, textura a/m, m/r, mc/r/r, A fraco, excessivamente/bem- moderadamente-bem drenado, Ta, distrófico.

PVA11 - Argissolo Vermelho-Amarelo Raso, textura m/r, m/rc, mc/r, m/m, a/m, A húmico, proeminente, moderado, bem-excessivamente/bem drenado, Tb-Ta, distrófico.

PVA12 - Argissolo Vermelho-Amarelo Raso, textura m/r, A proeminente, húmico, rochoso, bem drenado, Tb-Ta, distrófico.

PVA13 – Argissolo Vermelho-Amarelo Raso, textura m/r, mc/r, A moderado, epipedregoso-endopedregoso- pedregoso, bem-moderadamente drenado, Tb-Ta, distrófico-eutrófico.

PVA14 - Argissolo Vermelho-Amarelo Raso, textura m/r, A moderado, pedregoso, rochoso, bem drenado, Ta, distrófico

PVA15 - Argissolo Vermelho-Amarelo Típico, textura m/m/r, m/m/rc, m/mc/rc,m/r/m, m/r/r, m/rc/rc, mc/rc/rc, mc/mc/rc; m/rc/r, ac/rc/r, mc/r/r, ac/rc/rc, a/m, A fraco, pouco profundo, profundo, bem-moderadamente-excessivamente/bem drenado, Tb-Ta, distrófico.

PVA16 – Argissolo Vermelho-Amarelo Típico, textura m/r/r, A fraco, rochoso, profundo, bem drenado, Tb, distrófico.

PVA17 – Argissolo Vermelho-Amarelo Típico, textura ac/m/r, m/r/r, rc/r/r, A fraco, epipedregoso-endopedregoso-pedregoso, profundo, bem-moderadamente-excessivamente/bem drenado, Tb-Ta, distrófico.

PVA18 - Argissolo Vermelho-Amarelo Típico, textura m/r, A fraco, epipedregoso, rochoso, pouco profundo, bem drenado, Ta, distrófico.

PVA19 - Argissolo Vermelho-Amarelo Típico, textura m/rc/r, m/r/r, A proeminente, moderado, rochoso, pouco profundo, profundo, bem drenado, Tb, distrófico.

PVA20 - Argissolo Vermelho-Amarelo Típico, textura mc/a/m, m/m/m, m/a/r, m/ac/rc, m/m/r, m/m/rc, m/mc/rc, mc/mc/rc, m/r/m, mc/rc/mc, m/r/r, m/r/rc, m/rc/rc, mc/r/r, mc/rc/r, mc/rc/rc, mc/r/m, a/mc/mc, ac/mc/mc, a/m/r, a/mc/rc, ac/r/r, m/mc/r, m/r/mc, rc/rc/rc, m/rc/rc, r/r/r, A chernozêmico, húmico, proeminente, moderado, pouco profundo, profundo, bem-moderadamente-excessivamente/moderadamente-excessivamente/bem drenado, Tb-Ta, eutrófico – distrófico.

PVA21 - Argissolo Vermelho-Amarelo Típico, textura m/r/r, m/a/r, A húmico, moderado, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

PVA22 - Argissolo Vermelho-Amarelo Típico, textura m/m/r, m/r/r, mc/r/r, mc/rc/rc, ac/r/m, mc/r, a/rc, A húmico, proeminente, moderado, epipedregoso-endopedregoso-pedregoso, pouco profundo, profundo, bem-moderadamente-excessivamente/bem drenado, Tb-Ta, distrófico.

CY - Cambissolo Flúvico Típico, textura m/m/m, A moderado, profundo, imperfeitamente drenado, Tb, distrófico.

CX1 - Cambissolo Háplico Gleissólico, textura r/a/m, A fraco, profundo, imperfeitamente drenado, Tb, distrófico.

CX2 - Cambissolo Háplico Gleissólico, textura r/r/r, m/m/m, A moderado, pouco profundo, imperfeitamente drenado, Tb, distrófico.

CX3 - Cambissolo Háplico Gleissólico, textura m/m/m, A proeminente, rochoso, profundo, imperfeitamente drenado, Tb, distrófico.

CX4 - Cambissolo Háplico Raso, textura m/m, mc/mc, r/r/r, r/r, A fraco, moderadamente drenado, Tb-Ta, distrófico.

CX5 - Cambissolo Háplico Raso, textura m/m/a, m/m/m, A fraco, epipedregoso-endopedregoso-pedregoso, moderadamente drenado, Tb-Ta, distrófico.

CX6 - Cambissolo Háplico Raso, textura m/m/m, A moderado, epipedregoso-endopedregoso-pedregoso, moderadamente drenado, Tb, distrófico.

CX7 - Cambissolo Háplico Raso, textura m/m, mc/mc, r/r/r, m/ac/rc, mc/rc/m, A moderado, proeminente, moderadamente drenado, Tb-Ta, distrófico

CX8 - Cambissolo Háplico Raso, textura m/m/m, A moderado, pedregoso, rochoso, moderadamente drenado, Tb, distrófico.

CX9 - Cambissolo Háplico Típico, Plíntico, textura m/m/m, mc/mc/mc, rc/mc/rc, r/r/r, m/m/a, mc/m/m, mc/rc/mc, A fraco, pouco profundo, profundo, moderadamente drenado, Tb-Ta, distrófico.

CX10 - Cambissolo Háplico Típico, textura m/m/m, mc/mc/mc; ac/rc/mc, m/r/r, r/r/r, a/m/a, ac/r/m, rc/r, A fraco, epipedregoso-endopedregoso-pedregoso, pouco profundo, moderadamente, excessivamente/moderadamente drenado, Tb-Ta, distrófico-eutrófico.

CX11 - Cambissolo Háplico Típico, textura m/m/m, A fraco, epipedregoso-endopedregoso-pedregoso, rochoso, pouco profundo, moderadamente drenado, Tb, distrófico.

CX12 - Cambissolo Háplico Típico, textura m/m/m, m/mc/mc, mc/m/m, mc/mc/mc; mc/r/r, mc/rc/rc, m/rc, mc/mc/s, r/r/r, rc/r/r, m/r/r, m/ac/rc, m/rc/mc, mc/ac/ac, ac/mc mc/rc/mc, mc/rc/r, m/rc/rc, r/r/m, ac/rc, m/mc, m/r, m/m, mc/mc, mc/r, r/a/m, a/rc/m, A proeminente, moderado, pouco profundo, profundo, moderadamente drenado, excessivamente/moderadamente drenado, Tb-Ta, distrófico-eutrófico.

CX13 - Cambissolo Háplico Típico, textura mc/mc/mc, m/m/m, mc/rc/rc, r/r/r, m/r/r, A proeminente, moderado, pouco profundo, profundo, imperfeitamente drenado, Tb-Ta, distrófico.

CX14 - Cambissolo Háplico Típico, Plíntico, textura m/m/m, mc/m/m, mc/mc/mc, m/r/r, r/r/r; mc/m/r, mc/rc/rc, a/r/s, a/r/r, a/m/m, mc/mc, m/r, mc/rc, mc/r, rc/rc, m/rc, A proeminente, moderado, epipedregoso-endopedregoso-pedregoso, pouco profundo, profundo, moderadamente-excessivamente/moderadamente drenado, Tb-Ta, distrófico-eutrófico.

CX15 - Cambissolo Háplico Típico, textura m/m/m, m/rc, m/r, mc/mc, A moderado, rochoso, pouco profundo, moderadamente drenado, Tb, distrófico.

CX16 - Cambissolo Háplico Típico, textura m/r/r, A moderado, rochoso, pouco profundo, imperfeitamente drenado, Ta, distrófico.

CX17 - Cambissolo Háplico Típico, textura m/m/m, mc/m/m, A moderado, epipedregoso-endopedregoso-pedregoso, rochoso, pouco profundo, moderadamente drenado, Ta, distrófico.

CX18 - Cambissolo Háplico Adensado, textura r/r, A fraco, pouco profundo, imperfeitamente drenado, Ta, distrófico.

CX19 - Cambissolo Háplico Adensado, textura mc/rc, m/r, A fraco, pouco profundo, moderadamente drenado, Ta, distrófico

CX20 - Cambissolo Háplico Adensado, textura mc/rc, mc/mc, m/m, m/r/r, A moderado, pouco profundo, moderadamente drenado, Tb-Ta, eutrófico

CX21 - Cambissolo Háplico Adensado, textura m/m/m, mc/rc/rc, A moderado, pouco profundo, profundo, imperfeitamente drenado, Ta, distrófico.

CX22 - Cambissolo Háplico Adensado, textura mc/mc, A moderado, rochoso, pouco profundo, moderadamente drenado, Tb-Ta, distrófico-eutrófico.

CH1 - Cambissolo Húmico Gleissólico, textura m/m/m, pedregoso, pouco profundo, imperfeitamente drenado, Ta, distrófico.

CH2 - Cambissolo Húmico Raso, textura mc/mc/mc, moderadamente drenado, Tb, distrófico.

CH3 - Cambissolo Húmico Típico, textura m/m/m, mc/r/r, rc/rc/rc, m/m/m, mc/mc/mc, m/r/r, ac/rc/mc, m/ac/mc, mc/ac/rc, m/r/r, pouco profundo, profundo, moderadamente-excessivamente/moderadamente drenado, Tb-Ta, distrófico-eutrófico.

CH4 - Cambissolo Húmico Típico, textura m/r/r, a/r/m, m/mc, epipedregoso, pouco profundo, moderadamente-excessivamente/moderadamente drenado, Tb, distrófico.

MT1 - Chernossolo Argilúvico Gleissólico, textura m/r/r, profundo, imperfeitamente drenado.

MT2 - Chernossolo Argilúvico Epiáquico, textura r/r/r, epipedregoso, profundo, imperfeitamente drenado.

MT3 - Chernossolo Argilúvico Típico, textura m/r/r, profundo, bem drenado.

MT4 - Chernossolo Argilúvico Típico, textura m/r, m/r/r, epipedregoso, pouco profundo, bem drenado.

MT5 - Chernossolo Argilúvico Adensado, textura m/r, endopedregoso, profundo, moderadamente drenado.

MX1 - Chernossolo Háplico Típico, textura r/r/r; m/m/m, pouco profundo, bem-moderadamente drenado.

MX2 - Chernossolo Háplico Típico, textura m/m/m, mc/mc/mc, epipedregoso-pedregoso, pouco profundo, profundo, bem-moderadamente drenado.

GX1 - Gleissolo Háplico Típico, textura r/r/r, A fraco, profundo, Tb, distrófico.

GX2 - Gleissolo Háplico Típico, textura r/r/r, A moderado, profundo, mal drenado, Tb, distrófico.

GX3 - Gleissolo Háplico Plíntico, textura m/m/m, A moderado, profundo, Ta, distrófico.

GM - Gleissolo Melânico Típico, textura m/m/m, A proeminente, profundo, Ta, distrófico.

TC1 - Luvissolo Crômico Raso, textura mc/rc, A moderado, epipedregoso-endopedregoso-pedregoso, , raso, bem drenado.

TC2 - Luvissolo Crômico Típico, textura m/r/r, m/rc/rc, mc/rc/rc; m/m/r, m/r/m, m/m/m, A húmico, proeminente, moderado, pouco profundo, profundo, bem-moderadamente drenado.

TC3 - Luvissolo Crômico Típico, textura m/r/r, r/r/r, m/rc/mc, A moderado, epipedregoso-pedregoso, pouco profundo, profundo, bem drenado.

TX1 - Luvissolo Háplico Epiáquico, Gleissólico, textura m/r/r, a/m/m, m/m/r, A proeminente, moderado, pouco profundo, profundo, imperfeitamente, excessivamente/imperfeitamente drenado.

TX2 - Luvissolo Háplico Raso, textura ac/mc, m/r, A proeminente, moderado, endopedregoso-pedregoso, moderadamente-excessivamente/moderadamente drenado.

TX3 - Luvissolo Háplico Raso, textura m/r, A moderado, bem drenado.

TX4 - Luvissolo Háplico Típico, textura m/m/r, m/r/r, mc/rc/mc, r/r/r, A proeminente, moderadopouco profundo, profundo, bem-moderadamente drenado.

TX5 - Luvissolo Háplico Típico, textura m/r/r; m/m/r, A proeminente, moderado, pouco profundo, profundo, imperfeitamente drenado.

TX6 - Luvissolo Háplico Típico, textura mc/m/r, A moderado, pedregoso, profundo, bem drenado.

TX7 - Luvissolo Háplico Típico, textura m/r, A fraco, pouco profundo, moderadamente drenado.

TX8 - Luvissolo Háplico Típico, textura m/r, r/r/r, A húmico, moderado, epipedregoso, pouco profundo, imperfeitamente drenado.

TX9 - Luvissolo Háplico Típico, textura r/r/r, A proeminente, epipedregoso, rochoso, pouco profundo, imperfeitamente drenado.

TX10 - Luvissolo Háplico Adensado, textura r/r, r/r/r, m/r, A proeminente, moderado, pouco profundo, imperfeitamente drenado.

RY - Neossolo Flúvico Típico, textura m/m/m, A moderado, profundo, imperfeitamente drenado, Tb, distrófico.

RL1 - Neossolo Litólico Típico, textura m/m, mc/mc, A fraco, bem-moderadamente drenado.

RL2 - Neossolo Litólico Típico, textura m/m, r, m, A fraco, epipedregoso-endopedregoso-pedregoso, bem-moderadamente drenado.

RL3 - Neossolo Litólico Típico, textura mc/mc, A fraco, epipedregoso-endopedregoso-pedregoso, rochoso, bem-moderadamente drenado.

RL4 - Neossolo Litólico Típico, textura m/m, m/mc, m, A chernozêmico, moderado, rochoso, bem-moderadamente drenado.

RL5 - Neossolo Litólico Típico, textura ac/ac, mc/ac, m/m, mc/mc, m, mc, ac, a, A chenozêmico, húmico, proeminente, moderado, bem-moderadamente drenado.

RL6 - Neossolo Litólico Típico, textura m/m, mc/mc, m, rc/rc, mc, A húmico, proeminente, moderado, epipedregoso-endopedregoso-pedregoso, bem-moderadamente drenado.

RL7 - Neossolo Litólico Típico, textura m/m, mc/mc, A proeminente, moderado, epipedregoso-endopedregoso-pedregoso, rochoso, bem-moderadamente drenado.

RQ1 - Neossolo Quartzarênico Típico, A fraco, pouco profundo, profundo, excessivamente drenado.

RQ2 - Neossolo Quartzarênico Típico, A proeminente, húmico, moderado, pouco profundo, profundo, excessivamente drenado.

RQ3 - Neossolo Quartzarênico Típico, A moderado, endopedregoso, profundo, excessivamente drenado.

RQ4 - Neossolo Quartzarênico Típico, A proeminente, profundo, imperfeitamente drenado.

RR1 - Neossolo Regolítico Típico, textura m/a/a, m/m/a, m/ac/ac, ac/ac/ac, mc/ac/ac, m/m/a, mc/a, m/a/m, m/ac, r/r, m/a, m/mc, mc/ac, m/, m/m, A chernozêmico, húmico, proeminente, moderado, bem-moderadamente drenado, Tb-Ta, distrófico-eutrófico.

RR2 - Neossolo Regolítico Típico, textura m/a/a, mc/mc, m/r, m/mc, m/m/m, mc/mc/mc, A húmico, proeminente, moderado, epipedregoso-endopedregoso-pedregoso, bem-moderadamente drenado, Ta, distrófico-eutrófico.

RR3 - Neossolo Regolítico Típico, textura m/m, mc/r, A fraco, bem-moderadamente drenado, Ta-Tb, distrófico-eutrófico.

RR4 - Neossolo Regolítico Típico, textura m/m/m, mc/m/m, A fraco, epipedregoso-endopedregoso-pedregoso, bem-moderadamente drenado, Tb-Ta, distrófico-eutrófico.

RR5 - Neossolo Regolítico Típico, textura m/m/m, m/a, m/a/a, A proeminente, moderado, rochoso, bem-moderadamente drenado, Ta, distrófico.

RR6 - Neossolo Regolítico Típico, textura m/m/m, m/m, A proeminente, moderado, epipedregoso, pedregoso, rochoso, bem-moderadamente drenado, Ta, eutrófico.

RR7 - Neossolo Regolítico Adensado, textura mc/rc, A proeminente, endopedregoso, moderadamente profundo, Tb, distrófico.

RR8 - Neossolo Regolítico Típico, textura mc/mc, A moderado, imperfeitamente drenado, Tb-Ta, eutrófico-distrófico.

RR9 - Neossolo Regolítico Adensado, textura ac/r, A fraco, epipedregoso, moderadamente drenado, Tb-Ta, eutrófio-distrófico.

NX1 - Nitossolo Háplico Típico, textura r/r/r, rc/r/r, A moderado, pouco profundo, profundo, bem drenado, Tb-Ta, distrófico.

NX2 - Nitossolo Háplico Típico, textura r/r/r, A fraco, endopedregoso, pouco profundo, bem drenado, Tb, distrófico.

NV1 - Nitossolo Vermelho Raso, textura rc/r, A moderado, bem drenado, Tb, distrófico.

NV2 - Nitossolo Vermelho Típico, textura r/r/r, rc/rc/rc, A fraco, profundo, bem drenado, Tb, distrófico.

NV3 - Nitossolo Vermelho Típico, textura r/r/r, rc/rc/r, r/rc/r, A moderado, húmico, profundo, bem drenado, Tb, distrófico.

NV4 - Nitossolo Vermelho Típico, textura r/r/r, A moderado, epipedregoso-endopedregoso-pedregoso, profundo, bem drenado, Tb, distrófico.

SX1 - Planossolo Háplico Gleissólico, textura m/m/m, m/mc/mc, m/m/r, m/r/r, r/m/m, mc/r/r, m/rc/r, m/m/rc, m/mc/r, m/r, A chernozêmico, húmico, proeminente, moderado, pouco profundo, profundo, mal drenado, distrófico-eutrófico.

SX2 - Planossolo Háplico Gleissólico, textura m/m/r, m/r/r, mc/r/r, A fraco, profundo, mal drenado, distrófico-eutrófico.

SX3 - Planossolo Háplico Típico, Raso, textura m/m/r, m/r/r, m/a/r, m/r, mc/r/r, r/r/r, m/rc/rc, m/r/rc, A chernozêmico, proeminente, moderado, moderadamente profundo, profundo, imperfeitamente, mal drenado, distrófico-eutrófico.

SX4 - Planossolo Háplico Típico, textura m/m/r, A proeminente, endopedregoso, profundo, imperfeitamente drenado, distrófico.

SX5 - Planossolo Háplico Típico, textura m/m/r, A fraco, pouco profundo, imperfeitamente drenado, eutrófico.

FF1 - Plintossolo Pétrico Concrecionário, Raso, textura m/m/m, A fraco, moderadamente drenado, Tb, distrófico

FF2 - Plintossolo Pétrico Êndico, textura m/m/m, A moderado, pouco profundo, moderadamente drenado, Tb, distrófico.

FT1 - Plintossolo Argilúvico Típico, textura a/r/r, A moderado, pouco profundo, excessivamente/moderadamente drenado, Tb, distrófico.

FT2 - Plintossolo Argilúvico Adensado, textura m/r, A fraco, pouco profundo, imperfeitamente drenado.

FT3 - Plintossolo Argilúvico Adensado, textura m/r, A moderado, pouco profundo, imperfeitamente drenado.

FX1 - Plintossolo Háplico Típico, textura ac/ac/ac, A moderado, pouco profundo, excessivamente drenado, Tb, distrófico.

FX2 - Plintossolo Háplico Raso, textura m/s/r, A fraco, moderadamente drenado, Tb, distrófico.

LA - Latossolo Amarelo Típico, textura m/m/m, A moderado, distrófico.

LVA - Latossolo Vermelho-Amarelo Típico, textura m/m/m, A moderado, distrófico.

Uma grande variabilidade de classes de solos e UMPs foi identificada na escala de mapeamento deste estudo. Esta variabilidade é resultante de diferenças principalmente no material de origem e nas relações solo-paisagem nas regiões estudadas (CASTRO et al., 2010; STRECK et al., 2008). Na Tabela 6 encontram-se as UMPs e suas respectivas expressões geográficas.

Tabela 6 UMPs e suas respectivas extensões.

UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%
CH1	4,5	0,01	CX2	55,6	0,10	FT2	230,8	0,42	MX1	233,9	0,43
CH2	267,6	0,49	CX20	49,5	0,09	FT3	190,0	0,35	MX2	60,1	0,11
CH3	228,9	0,42	CX21	308,8	0,57	FX1	9,5	0,02	NV1	24,1	0,04
CH4	21,3	0,04	CX22	42,6	0,08	FX2	23,1	0,04	NV2	431,4	0,79
CX1	34,0	0,06	CX3	16,9	0,03	GM	70,7	0,13	NV3	657,0	1,20
CX10	432,0	0,79	CX4	164,0	0,30	GX1	17,0	0,03	NV4	43,6	0,08
CX11	34,6	0,06	CX5	129,5	0,24	GX2	18,3	0,03	NX1	63,3	0,12
CX12	3463,7	6,34	CX6	64,3	0,12	GX3	54,7	0,10	NX2	81,0	0,15
CX13	362,3	0,66	CX7	140,2	0,26	LA	25,5	0,05	PA01	113,3	0,21
CX14	2272,5	4,16	CX8	31,3	0,06	LVA	67,3	0,12	PA02	19,0	0,03
CX15	366,6	0,67	CX9	658,2	1,21	MT1	33,1	0,06	PA03	11,1	0,02
CX16	286,7	0,53	CY	10,9	0,02	MT2	107,9	0,20	PA04	103,6	0,19
CX17	88,9	0,16	FF1	9,2	0,02	MT3	16,2	0,03	PA05	1007,7	1,85
CX18	135,2	0,25	FF2	8,8	0,02	MT4	86,5	0,16	PA06	188,7	0,35
CX19	531,7	0,97	FT1	24,5	0,04	MT5	13,4	0,02	PA07	100,4	0,18

Tabela 6, continua

UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%
PA08	170,6	0,31	PV10	352,7	0,65	PVA06	83,9	0,15	RQ1	331,1	0,61
PA09	93,4	0,17	PV11	65,4	0,12	PVA07	533,4	0,98	RQ2	569,5	1,04
PA10	51,3	0,09	PV12	907,2	1,66	PVA08	17,3	0,03	RQ3	40,0	0,07

PA11	1018,0	1,86	PV13	36,1	0,07	PVA09	26,1	0,05	RQ4	117,9	0,22
PA12	1238,8	2,27	PV14	13128,2	24,05	PVA10	55,9	0,10	RR1	2021,0	3,70
PA13	11,9	0,02	PV15	30,3	0,06	PVA11	251,3	0,46	RR2	364,8	0,67
PA14	16,3	0,03	PV16	994,1	1,82	PVA12	119,3	0,22	RR3	82,8	0,15
PA15	145,0	0,27	PV17	154,9	0,28	PVA13	84,2	0,15	RR4	126,9	0,23
PAC	365,0	0,67	PV18	133,6	0,24	PVA14	338,2	0,62	RR5	13,1	0,02
PV01	35,2	0,06	PV19	33,8	0,06	PVA15	510,8	0,94	RR6	508,6	0,93
PV02	392,8	0,72	PVA01	88,9	0,16	PVA16	18,4	0,03	RR7	102,1	0,19
PV03	343,8	0,63	PVA02	98,6	0,18	PVA17	141,4	0,26	RR8	61,4	0,11
PV04	42,8	0,08	PVA03	59,0	0,11	PVA18	48,5	0,09	RR9	225,2	0,41
PV05	19,7	0,04	PVA04	29,3	0,05	PVA19	49,7	0,09	RY	2,4	0,00
PV06	12,2	0,02	PVA05	27,5	0,05	PVA20	4473,0	8,19	SX1	1083,8	1,99

Tabela 6, continua

UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%	UMPs	Área (ha)	%
SX2	58,5	0,11	SX3	1584,1	2,90	SX4	44,7	0,08	SX5	54,7	0,10
TC1	31,3	0,06	TC2	435,2	0,80	TC3	90,6	0,17	TX01	245,3	0,45
TX02	114,3	0,21	TX03	28,6	0,05	TX04	421,6	0,77	TX05	238,7	0,44
TX06	14,3	0,03	TX07	25,0	0,05	TX08	155,9	0,29	PVA21	169,8	0,31
PVA22	394,2	0,72	RL1	176,4	0,32	RL2	91,4	0,17	RL3	51,9	0,10
RL4	515,3	0,94	RL5	1007,3	1,84	RL6	939,5	1,72	RL7	143,4	0,26
TX09	118,3	0,22	TX10	381,7	0,70						

Considerando apenas o primeiro e segundo níveis categóricos, as classes de solo com maior expressão geográfica foram: PV (16.900 ha), CX (9.668 ha), PVA (7.618 ha), PA (4.289 ha), RR (3.505 ha), RL (2.925 ha) e SX (2.825 ha). Já as UMPs de maior expressão geográfica foram PV14 (13.128 ha ou 24,05%), seguido de PVA20 (4.472 ha ou 8,19%), CX12 (3.463 ha ou 6,34%), CX14 (2.272 ha ou 4,16%), RR1 (2.021 ha ou 3,70%), SX3 (1.584 ha ou 2,90%) e PA12 (1.238 ha ou 2,27%). A diferença entre os Cambissolos acima citados consiste na presença de pedregosidade no CX14. No SX3 incluem-se além dos solos pouco profundos e profundos, os rasos. Isso porque o risco de anoxia inerente a esses solos imperfeitamente ou mal drenados sobrepuja a limitação quanto à profundidade, considerando a produtividade do eucalipto. Contudo, conclui-se que os solos de maior expressão geográfica nas áreas de estudo são basicamente típicos, porém com grande variabilidade quanto à textura e tipo de horizonte A. Grande variabilidade quanto à presença ou ausência de rochosidade, pedregosidade, classes de drenagem e profundidade também foi encontrada entre as classes de solos. Com exceção dos solos que ocorrem preferencialmente em relevo plano de várzea ou em relevos plano e suave ondulados (RY, CY, GX, GM, e alguns SX mal drenados), as demais classes de solo apresentaram considerável variabilidade quanto ao critério fase de relevo.

Ainda considerando as relações do solo com a paisagem, de modo geral, os solos nas porções mais elevadas, convexas ou côncavas, apresentam cores mais avermelhadas, enquanto que nas posições mais baixas mostram cores mais acinzentadas, e cores vermelho-amarelas nas porções intermediárias (STRECK et al., 2008). Um exemplo de uma hidrossequência comum nas áreas de estudo é apresentado na Figura 3, no horto florestal Guajuvira I. Argissolos Vermelhos típicos encontram-se nas posições mais elevadas e bem drenadas do terreno, seguidos de PVA típico nas porções intermediárias, e de PA gleissólico na parte mais baixa e mal drenada (Figura 3a). A partir do mapa de *hillshade*, o qual cria um relevo sombreado, considerando o ângulo de iluminação do sol e sombras, é possível notar a microdepressão local na qual se encontra o PA (Figura 3b). Esse tipo de feição do terreno foi observada frequentemente no levantamento de solos, no qual a posição mais côncava contribui para um maior acúmulo de água. Solos moderadamente a imperfeitamente drenados, quando ocorrem em relevos mais movimentados, estão relacionados a restrições de drenagem impostas pela presença de sedimentos pelíticos muito impermeáveis. Este fato, aliado a um leve abaciamento ou aplainamento local da área, colabora para uma maior restrição à drenagem (COSTA et al., 2009a).

A interação das cores e a umidade do solo permite uma série de inferências a respeito dos diferentes ambientes de solos, uma vez que a cultura do eucalipto é reconhecidamente sensível à deficiência de oxigênio (CURI, 2000), o que pode comprometer sua produtividade. Costa et al. (2009a) propôs uma decodificação quanto ao risco de anoxia a partir de levantamento pedológico, ou seja, considerando não apenas a paisagem, mas também atributos como textura, profundidade efetiva do *sólum*, presença de mosqueados, indícios de gleização, presença de caráter adensado e cascalhos/pedregosidade, no horto florestal Cerro Coroado (RS). As classes de risco de anoxia propostas correlacionaram-se com a mortalidade do eucalipto. A classe de solo no contexto da paisagem local, por integrar inúmeros atributos, funcionou como um estratificador adequado de ambientes no tocante ao risco à anoxia.

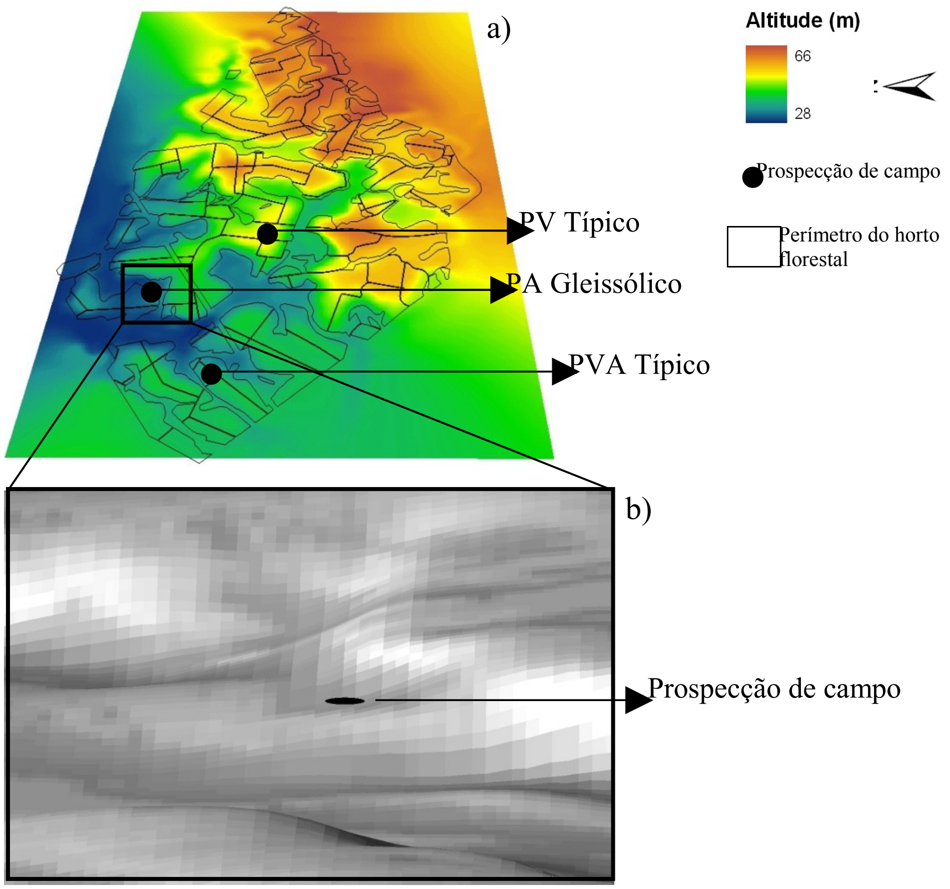

Figura 3 Modelo digital de elevação (a) e *hillshade* plotado em três dimensões (b) no horto florestal Guajuvira I

Os Argissolos apresentam aumento do teor de argila em profundidade, com consequente redução da permeabilidade e infiltração de água. No entanto, ocorrem menores perdas de água por ascensão capilar e a capacidade de armazenamento de água pode ser considerada como boa. Geralmente, limitações na drenagem natural são mais acentuadas quando há uma mudança textural abrupta ou há o contato lítico (solos rasos) (STRECK et al., 2008).

Neossolos ocorreram nas mais diversas condições de relevo e drenagem. Como características gerais, os Neossolos Litólicos e Regolíticos estão presentes principalmente nas porções mais acidentadas do relevo. Em termos de manejo, o mínimo de revolvimento do solo é sugerido devido à elevada suscetibilidade à erosão. A presença de rochosidade e pedregosidade, e baixa capacidade de armazenamento de água devido à pequena profundidade do solo, configuram outras importantes limitações. Desse modo, em áreas de Neossolos Litólicos, ou mesmo em outras classes de solos com pouca profundidade, cujo volume de armazenamento de água é menor, o plantio deve ser programado para o início do inverno onde há maior concentração de chuvas. No entanto, deve-se considerar que neste período também ocorre aumento de incidência de geadas, que é considerada fator climático importante quanto à restrição ao plantio de eucalipto no Rio Grande do Sul (HIGA; WREGE, 2011). Assim, o mais cedo possível, ou seja, mais próximo ao início do inverno, respeitando-se o risco potencial de geadas, deve ser feito o plantio de eucalipto nos solos mais rasos. Dentre os Neossolos, o Regolítico apresenta maior expressão geográfica, tanto nas áreas desse estudo, quanto no Rio Grande do Sul (STRECK et al., 2008). Já os Neossolos Quartzarênicos são arenosos em todo o perfil, apresentam baixa retenção de água (BOGNOLA et al., 2009), elevada taxa de lixiviação de nutrientes e alta suscetibilidade à erosão hídrica.

Nesse estudo, entre os solos situados em fase de relevo forte ondulado/montanhoso, 42% são Cambissolos, 13% são Neossolos Regolíticos e 12% são Neossolos Litólicos. Os Cambissolos ocorrem tipicamente em relevo acidentado, e comparando-os com os Neossolos Litólicos e Regolíticos, apresentam maior capacidade armazenamento de água. Possuem elevados teores de silte, baixa permeabilidade e encrostamento (selamento superficial) quando descobertos (RESENDE et al., 2007). Ocorre uma crescente amplitude relativa do tempo de preparo dos solos conforme aumenta a profundidade do *sólum*, ou seja, Neossolos Litólicos < Regolíticos < Cambissolos.

Os Gleissolos, que são mal drenados e considerados inaptos para o cultivo do eucalipto, ocorrem tipicamente em depressões do terreno em todo o Estado do Rio Grande do Sul, geralmente associados na paisagem aos Planossolos (STRECK et al., 2008). Os Planossolos possuem um aumento abrupto no teor de argila em pequena profundidade. Considerando as áreas de estudo, há alguns aspectos relevantes quanto ao manejo que são particulares desses solos. Os Planossolos Háplicos típicos situam-se principalmente no terço inferior das encostas em relevo plano/suave ondulado, possuem drenagem imperfeita e alto risco de anoxia. Esses solos, quando em relevo ondulado, o que ocorre com menor frequência, têm o risco de anoxia atenuado. A ocorrência de Planossolos, ou outros solos com drenagem imperfeita em relevos mais movimentados, é uma peculiaridade das regiões de estudo (STRECK et al., 2008), devido à presença de sedimentos pelíticos muito impermeáveis, conforme constatado nos trabalhos de campo. Já os Planossolos Háplicos gleissólicos, situados principalmente em relevo plano de várzea, são mal drenados e apresentam risco de anoxia muito elevado, sendo considerados inaptos para plantio de eucalipto em termos de sustentabilidade ambiental (COSTA et al., 2009b). Já os Plintossolos apresentaram drenagem moderada ou imperfeita, refletida pela cor variegada do horizonte B plíntico. Segundo Streck et al. (2008), esses solos ocupam porções mais elevadas do microrrelevo, ou em posições de transição entre várzeas e sopé das coxilhas.

Embora os Chernossolos possuam elevada fertilidade natural, sua aptidão agrícola pode ser limitada principalmente pelas condições de relevo e tipo de argila. Já os Luvissolos possuem argilas expansivas (esmectitas) na sua constituição, têm baixa condutividade hidráulica, dificultando o manejo e favorecendo o aumento do escoamento superficial (OLIVEIRA et al., 2008). Os Latossolos apresentaram extremamente pequena expressão geográfica na área estudada, estando presentes no extremo noroeste da região de estudo, no município de Santa Maria. Os Nitossolos possuem pouco incremento de argila em profundidade e cerosidade abundante, são bem drenados, e com razoáveis propriedades físicas (estrutura bem desenvolvida) e são argilosos em todo o perfil.

3.2 Unidades de manejo

Na Tabela 7 são apresentados os diferentes graus de limitação para cada UMP e respectiva fase de relevo, e as unidades de manejo.

Tabela 7 UMPs, graus de limitação para suscetibilidade à erosão (ΔE), deficiência de água (ΔA), deficiência de oxigênio (ΔO) e impedimentos ao manejo (ΔM) e unidades de manejo correspondentes

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
CH1_o	M	L	L	M	Restrita
CH2_fo,m	F	F	L	F	Restrita
CH2_o	M	F	L	L/M	Restrita
CH2_p,so	L	M	M	L/M	Restrita
CH3_fo,m	F	L	N	F	Restrita
CH3_o	M	L	N	L/M	Restrita
CH3_p,so	L	L	N	L/M	Regular
CH4_o	M	L	N	L/M	Restrita
CH4_p,so	L	L	N	L/M	Regular
CX01_p,so	L	N/L	M	M	Restrita
CX02_fo,m	F	L	L	F	Restrita
CX06_o	M	F	L	L/M	Restrita
CX06_p,so	L	M	M	L/M	Restrita
CX07_fo,m	F	F	L	F	Restrita
CX07_o	M	F	L	L/M	Restrita
CX07_p,so	L	M	M	L/M	Restrita
CX08_fo,m	F	F	L	F	Restrita
CX09_fo,m	F	L	N	F	Restrita
CX09_o	M	L	N	L/M	Restrita
CX09_o	M	L	N	L/M	Restrita
CX09_p,so	L	L	N	L/M	Regular
CX10_fo,m	F	L	N	F	Restrita
CX10_o	M	L	N	L/M	Restrita
CX10_o	M	L	N	L/M	Restrita
CX10_p,so	L	L	N	L/M	Regular
CX11_fo,m	F	L	N	F	Restrita
CX11_o	M	L	N	M	Restrita
CX12_fo,m	F	L	N	F	Restrita
CX12_o	M	L	N	L/M	Restrita

CX12_o	M	L	N	L/M	Restrita
CX12_p,so	L	L	N	L/M	Regular
CX13_fo, m	F	L	L	F	Restrita
CX13_o	M	L	L	M	Restrita
CX13_p,so	L	N/L	M	M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
CX14_fo, m	F	L	N	F	Restrita
CX14_fo, m	F	L	N	F	Restrita
CX14_o	M	L	N	L/M	Restrita
CX14_o	M	L	N	L/M	Restrita
CX14_p,so	L	L	N	L/M	Regular
CX15_fo, m	F	L	N	F	Restrita
CX15_o	M	L	N	M	Restrita
CX15_p,so	L	L	N	M	Restrita
CX16_fo, m	F	L	L	F	Restrita
CX16_o	M	L	L	M/F	Restrita
CX17_o	M	L	N	M	Restrita
CX17_p,so	L	L	N	M	Restrita
CX18_o	M	L	L	M/F	Restrita
CX18_p,so	L	N/L	M	M/F	Restrita
CX19_fo, m	F	L	N	F	Restrita
CX19_o	M	L	N	M	Restrita
CX19_p,so	L	L	N	M	Restrita
CX20_fo, m	F	L	L	F	Restrita
CX20_o	M	L	N	M	Restrita
CX21_fo, m	F	L	L	F	Restrita
CX21_o	M	L	L	M/F	Restrita
CX21_p,so	L	N/L	M	M/F	Restrita
CX22_o	M	L	N	M	Restrita
CX22_p,so	L	L	N	M	Restrita

CY	L	N/L	M	M	Restrita
FF1_p,so	L	M	M	L/M	Restrita
FF2_o	M	F	L	M/F	Restrita
FF2_p,so	L	M	M	M/F	Restrita
FT1_o	M	F	L	L/M	Restrita
FT1_p,so	L	M	M	L/M	Restrita
FT2_fo,m	F	L	L	F	Restrita
FT2_o	M	F	L	M	Restrita
FT2_p,so	L	N/L	N	M	Restrita
FT3_fo,m	F	L	L	F	Restrita
FT3_o	M	L	N	M	Restrita
FT3_p,so	L	N/L	N	M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
FX1_o	M	F	L	N	Restrita
FX1_p,so	M	M	M	N	Restrita
FX2_o	M	F	L	L/M	Restrita
FX2_p,so	L	M	M	L/M	Restrita
GM_p,so	N	N	F	F	Inadequada
GX1	N	N	F	F	Inadequada
GX2	N	N	F	F	Inadequada
GX3	N	N	F	F	Inadequada
LA_p,so	N	L	N	N	Adequada
LVA_p,so	N	L	N	N	Adequada
MT1_o	L	L	L	M	Restrita
MT1_p,so	N	N/L	M	M	Restrita
MT2_fo,m	F	L	L	F	Restrita
MT2_o	L	L	L	M	Restrita
MT2_p,so	N	N/L	M	M	Restrita
MT3_o	L	L	N	L	Regular
MT3_p,so	N	L	N	L	Adequada
MT4_o	L	L	N	L	Regular
MT4_p,so	N	L	N	L	Adequada

MT5_o	L	L	N	M	Restrita
MT5_p,so	N	L	N	M	Restrita
MX1_fo, m	F	L	N	F	Restrita
MX1_o	L	L	N	L	Regular
MX1_p,so	N	L	N	L	Adequada
MX2_o	L	L	N	L	Regular
NV1_o	M	F	L	L/M	Restrita
NV1_p,so	L	M	M	L/M	Restrita
NV2_fo,m	F	L	N	F	Restrita
NV2_o	L	L	N	L	Regular
NV2_p,so	N	L	N	L	Adequada
NV3_fo,m	F	L	N	F	Restrita
NV3_o	L	L	N	L	Regular
NV3_p,so	N	L	N	L	Adequada
NV4_fo,m	F	L	N	F	Restrita
NV4_o	L	L	N	L	Regular
NX1_o	L	L	N	L	Regular

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
NX2_o	L	L	N	L	Regular
NX2_p,so	N	L	N	L	Adequada
PA01_o	M	F	N	N	Restrita
PA01_p,so	M	F	N	N	Restrita
PA02_p,so	M	N/L	L	M	Restrita
PA03_o	M	F	N	N	Restrita
PA03_p,so	M	F	N	N	Restrita
PA04_o	L	L	L	M	Restrita
PA04_p,so	L	N/L	M	M	Restrita
PA04_p,so	N	N/L	M	M	Restrita
PA05_fo,m	F	L	L	F	Restrita
PA05_o	M	L	L	M	Restrita
PA05_o	M	L	L	M	Restrita
PA05_p,so	L	N/L	M	M	Restrita
PA06_o	M	F	L	L/M	Restrita
PA06_p,so	L	M	M	L/M	Restrita
PA07_fo,m	F	L	N	F	Restrita

PA07_o	L	L	N	L	Regular
PA07_p,so	N	L	N	L	Adequada
PA08_o	L	L	L	M	Restrita
PA08_o	L	L	L	M	Restrita
PA08_p,so	N	N/L	M	M	Restrita
PA09_o	L	L	N	L	Regular
PA09_p,so	N	L	N	L	Adequada
PA10_o	L	L	N	L	Regular
PA11_o	L	L	N	L	Regular
PA11_p,so	N	L	N	L	Adequada
PA12_fo,m	F	L	L	F	Restrita
PA12_fo,m	F	L	L	F	Restrita
PA12_o	L	L	L	M	Restrita
PA12_p so	N	N/L	M	M	Restrita
PA12_p,so	N	N/L	M	M	Restrita
PA13_o	M	L	N	M	Restrita
PA14_o	L	L	L	M	Restrita
PA15_o	L	L	L	M	Restrita
PA15_p,so	N	N/L	M	M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
PAC_p,so	N	N/L	M	M	Restrita
PV01_fo,m	F	F	N	L	Restrita
PV01_o	M	F	N	N	Restrita
PV02_o	L	L	N	M	Restrita
PV02_p,so	N	L	N	M	Restrita
PV03_fo,m	F	L	N	F	Restrita
PV03_o	L	L	N	M	Restrita
PV03_p,so	N	L	N	M	Restrita
PV04_o	L	L	N	M	Restrita
PV04_p,so	N	L	N	M	Restrita
PV05_o	M	F	L	M	Restrita
PV06_o	M	F	L	M	Restrita
PV07_o	L	L	L	M	Regular
PV07_p,so	N	N/L	M	M	Regular
PV08_o	M	F	L	L/M	Regular
PV08_o	M	F	L	L/M	Regular

PV08_p,so	L	M	M	L/M	Restrita
PV09_o	M	F	L	L/M	Restrita
PV10_fo,m	F	F	L	F	Restrita
PV10_o	M	F	L	L/M	Restrita
PV10_p,so	L	M	M	L/M	Restrita
PV11_fo,m	F	F	N	F	Restrita
PV11_o	M	F	L	L/M	Restrita
PV12_fo,m	F	L	N	F	Restrita
PV12_fo,m	F	L	N	F	Restrita
PV12_o	L	L	N	L	Regular
PV12_o	L	L	N	L	Regular
PV12_p,so	N	L	N	L	Adequada
PV13_fo,m	F	L	N	F	Restrita
PV13_o	L	L	N	L	Regular
PV13_o	L	L	N	L	Regular
PV13_p,so	N	L	N	L	Adequada
PV14_fo,m	F	L	N	F	Restrita
PV14_fo,m	F	L	N	F	Restrita
PV14_o	L	L	N	L	Regular
PV14_o	L	L	N	L	Regular

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
PV14_p,so	N	L	N	L	Adequada
PV14_p,so	N	L	N	L	Adequada
PV15_o	L	L	L	M	Restrita
PV15_p,so	N	N/L	M	M	Restrita
PV16_fo,m	F	L	N	F	Restrita
PV16_fo,m	F	L	N	F	Restrita
PV16_o	L	L	N	L	Regular
PV16_o	L	L	N	L	Regular
PV16_p,so	N	L	N	L	Adequada
PV16_p,so	N	L	N	L	Adequada
PV17_o	M	F	N	L/M	Restrita
PV17_p,so	L	M	N	L	Restrita
PV18_fo,m	F	F	N	L	Restrita
PV18_o	M	F	N	N	Restrita
PV18_p,so	M	F	N	N	Restrita

PV19_fo,m	F	L	N	F	Restrita
PV19_o	L	L	N	M	Restrita
PV19_p,so	N	L	N	M	Restrita
PVA01_o	L	L	N	M	Restrita
PVA01_p,so	N	L	N	M	Restrita
PVA02_fo,m	F	L	N	F	Restrita
PVA02_o	L	L	N	M	Restrita
PVA02_p,so	N	L	N	M	Restrita
PVA03_o	M	F	N	N	Restrita
PVA03_p,so	M	F	N	N	Restrita
PVA04_fo,m	F	F	L	F	Restrita
PVA04_o	M	F	N	N	Restrita
PVA05_o	M	F	N	N	Restrita
PVA06_o	M	F	N	N	Restrita
PVA06_p,so	M	F	N	N	Restrita
PVA07_o	L	L	L	M	Restrita
PVA07_p,so	N	N/L	M	M	Restrita
PVA08_o	N	L	M	L	Restrita
PVA08_p,so	N	N/L	M	L	Restrita
PVA09_o	M	F	L	L/M	Restrita
PVA09_p,so	L	M	M	L/M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
PVA10_fo,m	F	F	L	F	Restrita
PVA10_o	M	F	L	L/M	Restrita
PVA10_o	M	F	L	L/M	Restrita
PVA10_p,so	L	M	M	L/M	Restrita
PVA11_fo,m	F	F	L	F	Restrita
PVA11_o	M	F	L	L/M	Restrita
PVA11_p,so	L	M	M	L/M	Restrita
PVA12_o	M	F	L	M	Restrita
PVA12_p,so	L	M	M	M	Restrita
PVA13_o	M	F	L	L/M	Restrita
PVA13_p,so	L	M	M	L/M	Restrita
PVA14_o	M	F	L	M	Restrita
PVA14_p,so	L	M	M	M	Restrita
PVA15_fo,m	F	L	N	F	Restrita

PVA15_o	L	L	N	L	Regular
PVA15_p,so	N	L	N	L	Adequada
PVA16_fo,m	F	L	N	F	Restrita
PVA16_o	L	L	N	M	Restrita
PVA17_o	L	L	N	L	Regular
PVA17_p,so	N	L	N	L	Adequada
PVA17_p,so	N	N/L	N	L	Adequada
PVA18_fo,m	F	L	N	F	Restrita
PVA18_o	L	L	N	M	Restrita
PVA19_o	L	L	N	M	Restrita
PVA19_p,so	N	L	N	M	Restrita
PVA20_fo,m	F	L	N	F	Restrita
PVA20_fo,m	F	L	N	F	Restrita
PVA20_o	L	L	N	L	Regular
PVA20_p,so	N	L	N	L	Adequada
PVA21_o	L	L	L	M	Restrita
PVA21_p,so	N	N/L	M	M	Restrita
PVA22_fo,m	F	L	N	F	Regular
PVA22_fo,m	F	L	N	F	Restrita
PVA22_o	L	L	N	L	Adequada
PVA22_o	L	L	N	L	Regular
PVA22_p,so	N	L	N	L	Adequada

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
RL1_fo,m	F	F	L	F	Restrita
RL1_o	M	F	L	L/M	Restrita
RL2_fo,m	F	F	L	F	Restrita
RL2_o	M	F	L	L/M	Restrita
RL2_p,so	L	M	M	L/M	Restrita
RL3_o	M	F	L	M	Restrita
RL3_p,so	L	M	M	M	Restrita
RL4_fo,m	F	F	L	F	Restrita
RL4_o	M	F	L	M	Restrita
RL4_p,so	L	M	M	M	Restrita
RL5_fo,m	F	F	L	F	Restrita
RL5_o	M	F	L	L/M	Restrita
RL5_p,so	L	M	M	L/M	Restrita

RL6_fo,m	F	F	L	F	Restrita
RL6_o	M	F	L	L/M	Restrita
RL6_p,so	L	M	M	L/M	Restrita
RL7_fo,m	F	F	L	F	Restrita
RL7_o	M	F	L	M	Restrita
RL7_p,so	L	M	M	M	Restrita
RQ1_o	M	F	N	N	Restrita
RQ1_p,so	M	F	N	N	Restrita
RQ2_fo, m	F	F	N	L	Restrita
RQ2_o	M	F	N	N	Restrita
RQ2_p,so	M	F	N	N	Restrita
RQ3_o	M	F	N	N	Restrita
RQ4_o	M	F	N	N	Restrita
RQ4_p,so	M	F	N	N	Restrita
RR1_fo,m	F	L	L	F	Restrita
RR1_o	M	F	L	L/M	Restrita
RR1_p,so	L	M	M	L/M	Restrita
RR2_fo,m	F	L	L	F	Restrita
RR2_o	M	F	L	L/M	Restrita
RR2_p,so	L	M	M	L/M	Restrita
RR3_fo,m	F	L	L	F	Restrita
RR3_o	M	F	L	L/M	Restrita
RR3_p,so	L	M	M	L/M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
RR4_o	M	F	L	L/M	Restrita
RR5_o	M	F	L	M	Restrita
RR5_p,so	L	M	M	M	Restrita
RR6_fo,m	F	L	L	F	Restrita
RR6_o	M	F	L	M	Restrita
RR6_p,so	L	M	M	M	Restrita
RR7_o	M	F	L	M	Restrita
RR7_p,so	L	M	M	M	Restrita
RR8_fo,m	F	L	L	F	Restrita
RR8_o	M	F	L	M	Restrita
RR8_p,so	L	M	M	M	Restrita

RR9_fo,m	F	L	L	F	Restrita
RR9_o	M	F	L	M	Restrita
RR9_p,so	L	M	M	M	Restrita
RY	N	N/L	M	M	Restrita
SX1_o	L	N	F	F	Inadequada
SX1_p,so	N	N	F	F	Inadequada
SX2_p,so	N	N	F	F	Inadequada
SX2_p,so	N	N	F	F	Inadequada
SX3_o	M	L	L	L	Restrita
SX3_o	M	L	L	M	Restrita
SX3_p,so	L	N/L	M	M	Restrita
SX3_p,so	N	N/L	M	M	Restrita
SX4_o	M	L	N	M	Restrita
SX4_p,so	N	N/L	N	M	Restrita
SX5_p,so	N	N/L	N	M	Restrita
TC1_o	M	F	L	L/M	Restrita
TC2_o	L	L	N	L	Regular
TC2_p,so	N	L	N	L	Adequada
TC3_o	L	L	N	L	Regular
TC3_p,so	N	L	N	L	Adequada
TX01_fo,m	F	L	L	F	Restrita
TX01_o	L	L	L	M	Restrita
TX01_p,so	N	N/L	M	M	Restrita
TX02_o	M	F	L	L/M	Restrita
TX02_p,so	L	M	M	L/M	Restrita

Tabela 7, continua

UMP	ΔE	ΔA	ΔO	ΔM	Unidades de Manejo
TX03_p,so	L	M	M	L/M	Restrita
TX04_o	L	L	N	L	Regular
TX04_p,so	N	L	N	L	Adequada
TX05_o	L	L	L	M	Restrita
TX05_p,so	N	N/L	M	M	Restrita
TX06_fo,m	F	L	N	F	Adequada
TX06_p,so	N	L	N	L	Adequada
TX07_p,so	N	L	N	L	Adequada
TX08_o	L	L	L	M	Restrita
TX08_p,so	N	N/L	M	M	Restrita

TX09_fo,m	F	L	L	F	Restrita
TX09_o	L	L	L	M/F	Restrita
TX10_fo m	F	L	L	F	Restrita
TX10_fo,m	F	L	L	F	Restrita
TX10_o	L	L	L	M/F	Restrita
TX10_p,so	N	N/L	M	M/F	Restrita

N – nulo; L: ligeiro; M – moderado; F – forte

Um porcentual de 20% (10.841 ha) das áreas destinadas ao plantio foram classificadas como adequadas, englobando solos profundos e moderadamente profundos com horizonte B textural, nítico ou latossólico, bem ou moderadamente drenados e em relevo plano/suave ondulado. Segundo Food and Agriculture Organization of the United Nations - FAO (1981), o eucalipto apresenta maiores produções em solos de boa drenagem e férteis. Essa afirmativa corrobora com os estudos de Castro et al. (2010), onde solos maduros, ou seja, com horizonte B textural, bem drenados (Argissolos Vermelhos e Argissolos Vermelho-Amarelos) apresentaram maior incremento médio anual no Rio Grande do Sul.

Já as unidades de manejo enquadradas como regulares representaram 27% (14.706 ha) da área, contemplando as mesmas classes de solo que a unidade de manejo adequada, no entanto, em relevo ondulado. Este aumento na declividade implica principalmente em um aumento na suscetibilidade à erosão. Nestas unidades de manejo foram incluídos também os solos com horizonte Bi em relevo plano/suave ondulado, bem ou moderadamente drenados, moderadamente profundos ou profundos.

As unidades de manejo enquadradas como restritas representam 51% da área (27.723 ha), nas quais os solos contém limitações relacionadas à drenagem (imperfeitamente drenados), rochosidade, adensamento, horizonte plíntico e elevado teor de areia (solos arênicos ou Neossolos Quartzarênicos). E ainda, solos em relevo forte ondulado/montanhoso, independente de outras características, foram incluídos nessa unidades de manejo. Solos sem horizonte B ou rasos estão também inclusos.

Em solos com drenagem imperfeita, o preparo com grade *bedding*, ou o relevo mais movimentado, conforme critérios usados no ΔO, podem reduzir a deficiência de oxigênio. Com relação ao adensamento, que é resultante da pedogênes do solo, embora as chuvas sejam bem distribuídas nas áreas mapeadas, secas episódicas podem agravá-lo, dificultando o manejo, o desenvolvimento do sistema radicular e a infiltração de água. O uso de subsoladores seria uma alternativa para o rompimento desta camada adensada, melhorando o ambiente para uma maior exploração de volume de solo, água e nutrientes pelo sistema radicular (FINGER et al., 1996). Finger et al. (1996) encontraram efeito positivo com o uso de subsoladores em termos de crescimento do eucalipto, número de plantas vivas e produção de madeira na região de Guaíba (RS).

Os solos arênicos e o Neossolo Quartzarênico possuem grau nulo de limitação quanto aos impedimentos a mecanização. Uma espessa camada superficial arenosa facilita o trabalho dos implementos agrícolas até uma maior profundidade (STRECK et al., 2008). No entanto, estes solos possuem elevado grau de limitação quanto à suscetibilidade à erosão e deficiência de água (RESENDE et al., 2007). Para Raston (1967), o crescimento das árvores se eleva com o aumento do teor de silte e argila, devido a um suprimento mais favorável de água e nutrientes, até um ponto em que o acréscimo de partículas finas compromete a aeração do solo.

Segundo Carmo et al. (1990), áreas mais declivosas apresentam maior dificuldade de implantação, exploração e manejo sustentável do povoamento florestal, uma vez que esses solos geralmente são mais rasos, mais secos e mais propensos à erosão. Esses solos devem, portanto, ser submetidos a técnicas de manejo menos intensivas (BRAGA et al., 1999), como o cultivo mínimo do solo, com preparo restrito às covas de plantio (COSTA et al., 2009), e manutenção de resíduos da cultura que promovam o aumento da matéria orgânica (GONÇALVES et al., 2004). Essas considerações estão mais relacionadas a solos em relevo forte ondulado/montanhoso.

Outra característica do solo de grande influência no suprimento de água e no livre crescimento do sistema radicular é a profundidade efetiva do solo. A presença de camadas de impedimento físico, como horizonte plíntico, adensado, ou outros horizontes de baixa permeabilidade afeta o padrão de crescimento das árvores (GONÇALVES; DEMATTÊ; COUTO, 1990), se o manejo silvicultural não for adquado.

Já os solos considerados como inadequados ao plantio de eucalipto totalizam 2% (1.301 ha) da área, lembrando que não foram incluídos nesse estudo áreas de preservação permanente ou Neossolos Litólicos rochosos. Nesta unidade estão incluídos os Planossolos Háplicos Gleissólicos, Gleissolos Háplicos e Melânicos, presentes principalmente em relevo plano/suave ondulado ou em relevo plano de várzea. Tendo-se em mente a sustentabilidade ambiental, bem como a aptidão desses solos para o plantio de arroz irrigado por inundação, que é amplamente difundido no estado do Rio Grande do Sul, esses solos não são recomendados para o plantio de eucalipto (COSTA et al., 2009c). Outro fator considerado é que o eucalipto é extremamente sensível à deficiência de oxigênio (CURI, 2000), o que pode causar a mortalidade de plantas em alguns hortos florestais, e está diretamente correlacionado com a drenagem do solo (COSTA et al., 2009a). Esta limitação por anoxia tende a ser mais dramática em anos mais chuvosos e em plantios mais recentes, pois as raízes do eucalipto jovem retiram menos água do solo, sendo mais sensíveis.

O preparo adequado de solo pode modificar as condições naturais vindo a favorecer o desenvolvimento da cultura da exploração florestal (FINGER et al., 1996), minimizando as limitações e favorecendo uma maior produtividade e sustentabilidade da exploração florestal. Como exemplo, Oliveira (2008), em estudos na sub-bacia Terra Dura, observou maiores valores de perdas de solo para os Argissolos do que para os Cambissolos, mesmo estes últimos possuindo maior propensão à erosão em decorrência da menor profundidade efetiva e relevo mais acidentado. Esses resultados apontam para o efeito do manejo diferenciado para esses solos em relação à suscetibilidade natural à erosão, ocorrendo uma redução dos possíveis impactos.

4 CONCLUSÕES

A classe de solo e as fases de relevo se destacaram como adequadas estratificadoras de ambientes nos hortos florestais, as quais englobam grande variabilidade pedológica e pequena variação climática.

Quanto às classes de solo e suas limitações, destacam-se a suscetibilidade à erosão nas áreas mais acidentadas e o risco de anoxia nas áreas mais deprimidas da paisagem para o cultivo do eucalipto.

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ANEXOS

Perfil MIC 101 TD – Microbacia Terra Dura

DATA – 18/07/2008

CLASSIFICAÇÃO – CAMBISSOLO HÁPLICO Ta Distrófico típico epipedregoso A fraco textura m/r.

COORDENADAS UTM – 441.471 x 6.660.620 m, fuso 22, *datum SAD 69.*

ALTITUDE – 157 m.

SITUAÇÃO E DECLIVIDADE – Terço médio de encosta íngreme.

GEOLOGIA - Suíte Intrusiva Dom Feliciano, granito Serra do Herval, do Período Neoproterozóico (2500 Ma)

LITOESTATIGRAFIA - rochas ígneas e sienogranitos

EROSÃO – laminar ligeira.

DRENAGEM – bem drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – Floresta de eucalipto.

DESCRITO POR: João José Marques e Adélia Aziz Alexandre Pozza.

Descrição morfológica

O – 0 – 2 cm; transição plana e clara

Ap – 0-7 cm; bruno-avermelhado (5YR 5/4); textura média cascalhenta; fraca, pequena macia blocos subangulares; muito friável, não-plástica, não-pegajosa; transição plana e gradual.

Bi – 7 – 54 cm; bruno-avermelhado (5YR 5/4); textura muito argilosa; pequena moderada blocos angulares; dura, muito friável, ligeiramente plástico, ligeiramente pegajoso; transição plana e clara.

2Ab – 54 – 82 cm; bruno-avermelhado-escuro (5YR 3/3); textura argilosa cascalhenta; forte média blocos subangulares; cerosidade fraca e comum; ligeiramente dura muito friável, plástico e pegajoso; transição plana e gradual.
2CAb – 82 – 134 cm; vermelho (2,5YR 4/6); textura muito argilosa; forte média blocos subangulares; dura, firme, plástico pegajoso; cerosidade forte e abundante; transição ondulada e gradual.
2Cr – 134 – 183 cm+; vermelho (2,5YR 4/8); textura argilosa; moderada médios blocos angulares; cerosidade comum e moderada ligeiramente dura, friável, plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Observações em trincheira. Horizonte O – serrapilheira de eucalipto em graus variáveis de decomposição de muitas raízes. Raízes: comum e finas no O, poucas e finas no Ap e Bi, raras e finas no 2Ab e 2CAb e 2C. Pedregosidade no horizonte Bi. Crotovinas de material do 2Ab penetrando no 2CAb.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
Ap	0-7	370	250	260	120
Bi	7-54	170	40	110	680
2Ab	54-82	120	70	260	550
2CAb	82-134	90	40	150	720
2Cr	134-183+	320	150	180	350

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+Al	
		g kg^{-1}	%				cmol$_c$ dm^{-3}		g kg^{-1}
Ap	2,2	80	33	4,7	3,6	3,8	1,1	12,3	30,7
Bi	0,2	200	71	4,7	3,7	3,7	5,9	26,7	9,3
2AB	0,5	0	100	4,9	3,8	3,8	4,9	23,9	1,2
2CAb	0,2	0	100	4,9	3,7	3,8	4,9	23,9	2,9
2Cr	0,5	80	71	4,6	3,7	3,8	2,9	13,7	7,5

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P res.	P melich	P rem	N total	SB	T	m	V
	Ca	Mg	K								
	cmol$_c$ dm^{-3}		mg dm^{-3}			kg l^{-1}	%	cmol$_c$ dm^{-3}		%	
Ap	2,1	1,3	53	48,6	5,5	5,5	0,04	3,5	15,8	24	22,3
Bi	0,1	0,6	27	6,5	2,3	2,3	0,16	0,8	27,5	88	2,8
2AB	0,1	0,3	19	6,5	0,6	0,6	0,08	0,5	24,4	92	1,8
2CAb	0,1	0,5	22	4,3	0,6	0,6	0,10	0,7	24,6	88	2,7
2Cr	0,1	0,5	34	18,2	1,7	1,7	0,14	0,7	14,4	81	4,8

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
Ap	15	0,40	0,1	24,1	187,5	0,8	1,4	117,5
Bi	10	0,16	0	14,3	4,1	0,5	0,4	29,5
2AB	4,6	0,08	0	21,4	0,3	0,1	0,4	2,1
2CAb	7,4	0,13	0,1	18,9	0,3	0,1	0,3	1,5
2Cr	6,4	0,19	0,1	10,8	12,0	1,0	0,5	74,0

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
Ap	8,17	6,22	2,44	0,752	0,029	2,23	1,79	4,00
Bi	30,63	21,84	6,91	1,167	0,061	2,38	1,98	4,96
2AB	38,43	26,61	7,47	1,472	0,035	2,45	2,08	5,59
2CAb	38,57	26,55	7,73	1,241	0,048	2,47	2,08	5,39
2Cr	13,59	10,84	3,54	0,750	0,028	2,13	1,76	4,80

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	g kg^{-1}			
Ap	94	151	242	443
Bi	214	275	294	454
2AB	201	332	333	542
2CAb	233	304	334	526
2Cr	97	155	199	308

Perfil MIC 102 TD– Microbacia Terra Dura

DATA – 22/09/2008

CLASSIFICAÇÃO – ARGISSOLO VERMELHO Ta Distrófico típico A moderado textura r.

COORDENADAS UTM – 441.898 x 6.661.633 m, fuso 22, *datum SAD 69.*

ALTITUDE – 154 m.

SITUAÇÃO E DECLIVIDADE – Topo de encosta.

GEOLOGIA - Suíte Intrusiva Dom Feliciano, granito Serra do Herval do Período Neoproterozóico (2500 Ma)

LITOESTATIGRAFIA - rochas ígneas e sienogranitos.

EROSÃO – não aparente

DRENAGEM – bem drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – Floresta de eucalipto.

DESCRITO POR: João José Marques e Michele Duarte de Menezes.

Descrição morfológica

O – 0 – 1 cm; transição plana e clara

Ap – 0 - 23 cm; bruno-avermelhado (5YR 4/4); textura argilosa cascalhenta; moderada média blocos subangulares; macia, muito friável, plástica, pegajosa; transição plana e gradual.

BA – 23 – 36 cm; vermelho (2,5YR 4/6); textura muito argilosa; forte média blocos angulares; cerosidade comum e moderada; dura, friável, plástica e ligeiramente pegajosa; transição plana e gradual.

Bt1 – 36 – 77 cm; vermelho (2,5YR 4/8); textura muito argilosa; forte média blocos angulares; cerosidade moderada e comum; dura, firme, plástica e pegajosa; transição plana e gradual.
Bt2 – 77 – 187 cm+; bruno (7,5YR 5/4); textura argilosa; forte média blocos angulares; dura, firme, ligeiramente plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Dia nublado e chuvoso. Observações em trincheira. Ap: raízes médias e comuns. BA: raízes poucas e médias. Bt1: raízes poucas e médias. Bt2: raízes raras e finas; mosqueados amarelados cobrindo 10% do horizonte.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
Ap	0-23	320	160	170	350
BA	23 - 36	150	80	150	620
Bt1	36 - 77	170	60	110	660
Bt2	77 – 187+	180	70	150	600

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+Al	
		g kg^{-1}	%				$cmol_c$ dm^{-3}		g kg^{-1}
Ap	0,49	70	80	4,8	3,9	3,8	1,7	7,9	14,5
BA	0,24	100	84	4,4	3,8	3,8	3,6	17,1	8,7
Bt1	0,17	0	100	4,9	3,9	3,8	3,8	17,1	3,5
Bt2	0,25	0	100	5,2	3,9	3,8	3,5	17,1	0,6

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P res.	P melich	P rem	N total	SB	T	m	V
	Ca	Mg	K								
	$cmol_c$ dm^{-3}		mg dm^{-3}			kg l^{-1}	%	$cmol_c$ dm^{-3}		%	
Ap	1,2	0,7	47	7,3	1,7	20,5	1,8	2,1	10	45	20,7
BA	0,2	0,5	31	3,9	0,9	8,0	1,2	0,8	17,9	81	4,7
Bt1	0,1	0,5	58	2,7	0,6	4,3	0,8	0,8	17,9	83	4,4
Bt2	0,1	0,6	30	5,7	0,9	3,7	0,8	0,8	17,9	81	4,6

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
Ap	10	1,17	0,4	9,3	12,0	1,6	1,1	120,5
BA	13	1,26	0,2	19,5	0,7	0,9	0,6	22,0
Bt1	9,2	0,87	0,2	47,3	1,0	0,2	0,4	3,0
Bt2	10	1,02	0,2	32,6	0,5	0,1	0,3	1,0

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
Ap	12,74	10,95	4,19	0,882	0,054	1,98	1,59	4,10
BA	22,74	21,22	6,76	1,252	0,059	1,78	1,48	4,93
Bt1	25,77	22,44	6,97	1,175	0,053	1,95	1,63	5,05
Bt2	23,59	21,56	7,01	0,922	0,029	1,86	1,54	4,83

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	%			
Ap	149	160	192	220
BA	239	269	336	478
Bt1	207	272	309	478
Bt2	197	257	263	503

Perfil MIC 103 TD – Microbacia Terra Dura

DATA – 22/09/2008

CLASSIFICAÇÃO – ARGISSOLO VERMELHO-AMARELO A Ta Distrófico típico A moderado textura m/r moderadamente drenado.

COORDENADAS UTM – 441.436 x 6.660.957 m, fuso 22, *datum SAD 69.*

ALTITUDE – 125 m.

SITUAÇÃO E DECLIVIDADE – terço inferior de encosta.

GEOLOGIA - Suíte Intrusiva Dom Feliciano, granito Serra do Herval, do Período Neoproterozóico (2500 Ma)

LITOESTATIGRAFIA - rochas ígneas e sienogranitos

EROSÃO – não aparente

DRENAGEM – moderadamente drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – Floresta de eucalipto.

DESCRITO POR: João José Marques e Michele Duarte de Menezes.

Descrição morfológica

O – 1 – 0 cm; transição plana e gradual.

Ap1 – 0 - 4 cm; bruno (7,5YR 5/4); textura média cascalhenta; fraca pequena blocos subangulares; solta, muito friável, não-plástica, ligeiramente pegajosa; transição plana e gradual.

Ap2 – 4 – 16 cm; amarelo-brunado (10YR 6/6); textura média cascalhenta; fraca média blocos subangulares; macia, muito friável, ligeiramente plástica e ligeiramente pegajosa; transição plana e gradual.

2Apb – 16 – 27 cm;bruno-escuro (7,5YR 3/2); textura argilosa cascalhenta; fraca média blocos angulares; ligeiramente dura, friável, não-plástica e ligeiramente pegajosa; transição plana e gradual.
2AB - 27 – 43 cm; bruno (7,5YR 4/4); textura média; moderada média blocos angulares; ligeiramente dura, friável, não-plástica e ligeiramente pegajosa; transição plana e gradual.
2Bt – 43 – 117 cm; bruno-amarelado (10YR 5/4), vermelho-amarelado (5YR 5/6 – cor úmida e amassada); textura argilosa; forte média blocos angulares; cerosidade comum e moderada; dura, firme, ligeiramente plástica e ligeiramente pegajosa; transição plana e gradual.
2BC – 117 – 200 cm+; vermelho-amarelado (5YR 5/8 - cor úmida amassada); textura argilosa; forte média blocos angulares; cerosidade comum e moderada; ligeiramente dura, friável, plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Dia nublado e chuvoso. Observações em trincheira. Ap1: raízes finas e comuns. Ap2: raízes finas e comuns. 2Apb: raízes finas e comuns; possível horizonte A enterrado. 2AB: raízes finas e comuns. 2Bt: raízes finas e comuns; abundantes mosqueados (2,5YR 4/6); mosqueados compreendem 50% da área exposta. 2BC: raízes finas e raras; cor muito variegada com fragmentos do material de origem e zonas de gleização.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
Ap1	0 – 4	390	180	230	200
Ap2	4 – 16	310	220	210	260
2Apb	16 – 27	310	70	180	440
2AB	27 – 43	240	120	300	340
2Bt	43 – 117	170	90	290	450
2BC	117– 200+	180	100	320	400

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+Al	
		g kg^{-1}	%				cmol$_c$ dm^{-3}		g kg^{-1}
Ap1	1,2	40	80	4,4	3,7	3,6	1,5	13,7	29,6
Ap2	0,8	100	62	4,7	3,7	3,8	2,9	13,7	8,7
2Apb	0,4	70	84	4,9	3,8	3,9	3,6	19,1	11,6
2AB	0,9	90	85	4,9	3,8	3,8	3,5	17,1	7,0
2Bt	0,6	0	100	5,2	3,9	3,9	3,5	17,1	1,7
2BC	0,8	0	100	5,4	3,9	3,9	3,1	13,7	0,6

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P	P	P	N	SB	T	m	V
	Ca	Mg	K	res.	melich	rem	total				
	cmol$_c$ dm^{-3}		mg dm^{-3}			kg l^{-1}	%	cmol$_c$ dm^{-3}		%	
Ap1	2,4	0,7	109	8,9	2,8	33,1	2,6	3,4	17,1	31	19,9
Ap2	0,1	0,4	83	5,2	1,7	14	1,8	0,7	14,4	80	5,1
2Apb	0,1	0,3	67	3,6	0,9	3,7	1,6	0,6	19,7	86	3
2AB	0,1	0,2	59	1,1	0,6	3,3	1,2	0,5	17,6	88	2,7
2Bt	0,1	0,6	45	1,6	0,6	4,7	0,8	0,8	17,9	80	4,7
2BC	0,2	1,2	53	1,1	0,6	5,8	0,6	1,6	15,3	66	10,3

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
Ap1	7,4	0,66	0,4	10,3	26,5	0,8	1,8	116,5
Ap2	5,5	0,66	0,9	6,6	2,1	0,8	0,9	68,0
2Apb	6,4	0,66	0,3	9,3	0,4	0,7	0,6	44,5
2AB	6,4	0,7	0,2	13,3	0,2	0,3	0,4	19,0
2Bt	7,4	0,74	0,2	25,5	0,2	0,1	0,4	3,5
2BC	8,3	0,77	0,2	25,5	0,4	0,1	0,5	4,0

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
Ap1	8,73	8,10	2,56	0,584	0,035	1,83	1,52	4,96
Ap2	10,19	8,83	3,06	0,695	0,023	1,96	1,61	4,54
2Apb	20,80	17,38	5,89	1,095	0,035	2,03	1,67	4,64
2AB	25,52	20,68	6,55	1,103	0,042	2,10	1,74	4,96
2Bt	21,65	17,27	5,64	1,018	0,035	2,13	1,76	4,80
2BC	20,09	15,66	5,12	0,883	0,026	2,18	1,80	5,80

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	%			
Ap1	142	205	295	414
Ap2	105	161	214	289
2Apb	199	273	325	482
2AB	221	282	356	52
2Bt	170	251	291	429
2BC	164	236	280	410

Perfil MIC 104 PC – Microbacia Ponta das Canas

DATA – 29/09/2008

CLASSIFICAÇÃO – CAMBISSOLO HÁPLICO Ta distrófico úmbrico A proeminente textura a/r.

COORDENADAS UTM – 770.492 x 6.621.075 m, fuso 21, *datum SAD 69.*

ALTITUDE – 257 m.

SITUAÇÃO E DECLIVIDADE – terço superior de encosta íngreme.

GEOLOGIA – Cinturão Vila Nova, granito Panorama do período Paleozóico (267 Ma).

LITOESTATIGRAFIA – arenito e siltito.

EROSÃO – laminar ligeira.

DRENAGEM – moderadamente drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – floresta de eucalipto.

DESCRITO POR: João José Marques e Michele Duarte de Menezes.

Descrição morfológica

Ap – 0-20 cm; bruno-avermelhado (5YR 4/3); textura arenosa cascalhenta; moderada média blocos subangulares; ligeiramente dura, friável, não-plástica e não-pegajosa; transição plana e gradual.

2AB – 20 – 50 cm; bruno-avermelhado-escuro (5YR 3/2); textura arenosa muito cascalhenta; moderada média blocos sub-angulares; ligeiramente macia, friável, não-plástica e não-pegajosa; transição ondulada e clara.

2Bi/A – 50 – 84 cm; vermelho-amarelado (5YR 5/6 - cor úmida amassada); textura argilosa; moderada média blocos angulares; ligeiramente macia, friável, ligeiramente plástica e ligeiramente pegajosa; transição plana e gradual.

2Cr – 84 – 184 cm+; amarelo-avermelhado (5YR 6/6 - cor úmida amassada); textura argilosa cascalhenta; maciça; ligeiramente macia, muito friável, ligeiramente plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Observações em trincheira. Ap: raízes finas e comuns. 2Ab: raízes raras e finas. 2Bi/A: raízes raras e finas; observações referentes ao material Bi. 2Cr: raízes raras e finas.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
Ap	0 – 20	480	230	150	140
2AB	20 – 50	550	160	150	140
2Bi/A	50 – 84	360	140	150	350
2Cr	84 – 184+	330	160	160	350

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+Al	
		g kg^{-1}	%				cmol$_c$ dm^{-3}		g kg^{-1}
Ap	1,1	10	93	5,2	4,3	4,1	0,3	5,0	14,5
2AB	1,1	80	79	5,1	3,9	3,9	2,2	11,0	11,0
2Bi/A	0,4	0	100	5,2	3,9	3,9	3,3	12,3	1,2
2Cr	0,5	0	100	5,3	3,9	3,9	3,6	13,7	0,6

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P res.	P melich	P rem	N total	SB	T	m	V
	Ca	Mg	K								
	cmol$_c$ dm^{-3}		mg dm^{-3}			kg l^{-1}	%	cmol$_c$ dm^{-3}		%	
Ap	1,5	0,8	98	14,3	9,3	46	1,8	2,6	7,6	10	33,9
2AB	1,3	0,8	165	8,2	3,7	15,5	1,8	2,5	13,5	47	18,7
2Bi/A	0,3	0,2	115	0,7	1,4	10,7	0,6	0,8	13,1	80	6,1
2Cr	0,3	0,3	36	0,7	0,6	6,3	0,6	0,7	14,4	83	5,0

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
Ap	2,8	0,43	0,3	17,1	16,0	0,8	1,7	132,5
2AB	2,8	0,26	0,2	34,4	1,0	1,3	0,4	59,0
2Bi/A	2,8	0,3	0,2	36,2	0,2	0,1	0,4	9,5
2Cr	6,4	0,64	0,2	31,7	0,2	0,0	0,4	1,5

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
Ap	8,20	7,23	2,53	0,392	0,060	1,93	1,58	4,48
2AB	17,67	14,61	3,58	0,528	0,048	2,06	1,78	6,41
2Bi/A	18,81	15,64	3,58	0,345	0,014	2,04	1,78	6,86
2Cr	23,80	20,39	4,10	0,422	0,014	1,98	1,76	7,81

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	%			
Ap	86	118	216	232
2AB	143	192	258	355
2Bi/A	136	239	276	407
2Cr	166	274	375	458

Perfil MIC 105 PC – Microbacia Ponta das Canas

DATA – 29/09/2008

CLASSIFICAÇÃO – ARGISSOLO VERMELHO Distrófico típico A moderado textura m/r moderadamente drenado.

COORDENADAS UTM – 770.554 x 6.620.964 , fuso 21, *datum SAD 69.*

ALTITUDE – 266 m.

SITUAÇÃO E DECLIVIDADE – topo de encosta.

GEOLOGIA – cinturão Vila Nova, granito Panorama do período Paleozóico (267 Ma).

LITOESTATIGRAFIA – arenito e siltito.

EROSÃO – não aparenta.

DRENAGEM – bem drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – Floresta de eucalipto.

DESCRITO POR: João José Marques e Michele Duarte de Menezes.

Descrição morfológica

A1 – 0-5 cm; bruno-avermelhado (5YR 4/3); textura média; moderada média blocos sub-angulares; ligeiramente dura, friável, não-plástica e não-pegajosa; transição plana e gradual.

A2 – 5 – 17 cm; bruno-avermelhado (5YR 4/3); textura média; moderada média blocos sub-angulares; dura, friável, ligeiramente plástica e não-pegajosa; transição plana e gradual.

A3b – 17 – 54 cm; bruno-avermelhado-escuro (5YR 3/2); textura média; moderada média blocos sub-angulares; dura, friável, ligeiramente plástico e ligeiramente pegajosa; transição plana e gradual.

BA – 54 – 85 cm; bruno-avermelhado-escuro (2,5YR 3/4); textura muito argilosa; moderada média blocos angulares; cerosidade comum e moderada; macia, friável, plástica e ligeiramente pegajosa; transição plana e gradual.
Bt – 85 – 164 cm; vermelho (2,5YR 4/6); textura argilosa; moderada média blocos angulares; cerosidade forte e abundante; ligeiramente dura, friável, ligeiramente plástica e ligeiramente pegajosa; transição plana e gradual.
CB – 164 – 179 cm+; vermelho (2,5YR 4/8- cor úmida e amassada); textura argilosa cascalhenta; fraca muito pequena blocos angulares; cerosidade moderada e comum; macia, friável, não-plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Observações em trincheira. A1: raízes finas e abundantes. A2: raízes finas e comuns. A3b: raízes finas e comuns. BA: raízes finas e raras. Bt: raízes finas e raras. CB: raízes finas e raras. Presença de mosqueados de redução.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
A1	0 – 5	360	220	260	160
A2	5 – 17	390	190	210	210
A3b	17 – 54	380	130	150	340
BA	54 – 85	170	50	100	680
Bt	85 – 164	200	70	140	590
CB	164–179+	270	70	310	350

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+Al	
		g kg^{-1}	%				cmol$_c$ dm^{-3}		g kg^{-1}
A1	1,6	0	100	6,0	5,8	5,5	0	2,3	28,4
A2	1,0	110	48	5,4	4,1	4,0	1,2	7,9	12,2
A3b	0,4	30	91	5,4	4,1	3,9	2,2	12,3	10,4
BA	0,1	0	100	5,3	4,1	4,0	2,5	11.0	5,8
Bt	0,2	0	100	5,3	4,2	4,0	2,0	8,8	3,5
CB	0,9	0	100	5,3	4,2	4,0	1,9	7,9	1,2

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P	P	P	N	SB	T	m	V
	Ca	Mg	K	res.	melich	rem	total				
	$cmol_c\ dm^{-3}$		mg dm^{-3}			kg l^{-1}	%	$cmol_c\ dm^{-3}$		%	
A1	5,5	2,9	275	33,9	34,6	41	2,8	9,1	11,4	0	79,9
A2	1,6	0,6	126	6,6	2,5	24,8	1,8	2,5	10,4	32	24,3
A3b	1,9	0,7	61	3,2	1,7	7,0	1,2	2,8	15,1	44	18,5
BA	2,1	1,2	37	1,4	0,9	2,2	1,4	3,4	14,4	42	23,8
Bt	1,7	1,2	28	2,0	0,9	2,2	1,2	3,0	11,8	40	25,4
CB	1,0	1,3	28	3,2	0,9	3,1	1,0	2,4	10,3	44	23,2

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
A1	8,3	0,39	0,4	16,6	22,0	0,8	3,9	45,0
A2	2,8	0,33	0,2	19,5	8,0	1,6	0,8	83,0
A3b	6,4	0,56	0,3	27,7	0,9	1,5	0,5	42,5
BA	10	0,74	0,2	43,7	0,2	0,3	0,4	6,5
Bt	6,4	0,56	0,2	48,7	0,2	0,2	0,4	3,5
CB	5,5	0,56	0,2	19,5	0,3	0,0	0,4	2,5

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
A1	9,18	7,00	2,65	0,525	0,085	2,23	1,79	4,16
A2	9,40	8,28	2,94	0,551	0,054	1,93	1,57	4,42
A3b	13,52	12,01	3,79	0,640	0,035	1,91	1,59	4,98
BA	27,60	22,27	6,55	0,963	0,048	2,11	1,77	5,34
Bt	24,51	20,71	6,25	0,931	0,045	2,01	1,69	5,20
CB	21,66	17,58	6,69	0,754	0,029	2,09	1,68	4,13

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	%			
A1	151	173	260	444
A2	107	130	229	337
A3b	141	159	256	377
BA	237	313	362	562
Bt	204	287	309	473
CB	164	-	295	452

Perfil MIC 106 PC – Microbacia Ponta das Canas

DATA – 29/09/2008

CLASSIFICAÇÃO – CAMBISSOLO HÚMICO Ta Distrófico textura m/a/r.

COORDENADAS UTM – 770.880 x 6.621.333 , fuso 21, *datum SAD 69.*

ALTITUDE – 240 m.

SITUAÇÃO E DECLIVIDADE – terço médio de encosta.

GEOLOGIA – cinturão Vila Nova, granito Panorama do período Paleozóico (267 Ma).

LITOESTATIGRAFIA – arenito e siltito.

EROSÃO – não aparenta.

DRENAGEM – bem drenado.

VEGETAÇÃO NATIVA – floresta subtropical/Mata Subtropical Alta e Mata Subtropical Arbustiva.

USO ATUAL – floresta de eucalipto.

DESCRITO POR: João José Marques e Michele Duarte de Menezes.

Descrição morfológica

A – 0 – 22 cm; bruno-escuro (7,5YR 3/3) textura média cascalhenta; moderada média blocos sub angulares; ligeiramente dura, friável, não-plástica e não-pegajosa; transição plana e clara.

Ab – 22 – 83 cm; bruno-escuro (7,5YR 3/3); textura arenosa muito cascalhenta; moderada média blocos angulares; macia, muito friável, não-plástica e não-pegajosa; transição ondulada e gradual.

Bi – 83 – 100 cm; bruno (7,5YR 5/4); textura argilosa cascalhenta; moderada média blocos subangulares; macia, friável, ligeiramente plástica e ligeiramente pegajosa; transição plana e gradual.

Cr – 100 – 200 cm+; amarelo-avermelhado (5YR 6/6 - cor úmida amassada); textura argilosa cascalhenta; fraca grande blocos angulares; macia, friável, plástica e ligeiramente pegajosa.

OBSERVAÇÕES – Observações em trincheira. A: raízes finas e comuns. Ab: raízes finas e poucas. Bi: raízes finas e raras. Cr: raízes ausentes. Cor úmida amassada devido à variabilidade do material.

Tabela 1 Análise granulométrica (Prof. – profundidade, TFSA – terra fina seca ao ar)

Horizonte	Prof.	Composição granulométrica TFSA			
		Areia grossa	Areia fina	Silte	Argila
	cm	g kg^{-1}			
A	0 – 22	430	210	200	160
Ab	22 – 83	570	140	160	130
Bi	83 – 100	320	140	190	350
Cr	100–200+	350	110	190	350

Tabela 2 Relação silte/argila, argila dispersa em água (ADA), índice de floculação, pH em água, pH em KCl, pH em $CaCl_2$, acidez extraível e carbono orgânico (C org.)

Horiz.	%silte/ %argila	ADA	Índice de floculação	pH			Acidez extraível		C org
				H_2O	KCl	$CaCl_2$	Al	H+ Al	
		g kg^{-1}	%				cmol$_c$ dm^{-3}		g kg^{-1}
A	1,3	20	88	5,2	4,2	4,0	0,8	6,3	15,1
Ab	1,2	80	38	5,1	4,0	4,0	2,2	8,8	7,0
Bi	0,5	130	35	5,1	3,9	4,0	2,9	11	2,9
Cr	0,5	120	48	5,2	3,8	3,9	3,2	12,3	0,6

Tabela 3 Complexo sortivo, soma de bases (SB), CTC a pH 0,7 (T), saturação por alumínio (m) e saturação por bases (V)

Horizonte	Cátions trocáveis			P res.	P melich	P rem	N total	SB	T	m	V
	Ca	Mg	K								
	cmol$_c$ dm^{-3}		mg dm^{-3}			kg l^{-1}	%	cmol$_c$ dm^{-3}		%	
A	1,1	0,7	103	19,1	15,4	28,1	1,8	2,1	8,4	28	24,8
Ab	0,1	0,1	61	3,2	1,2	9,9	1,2	0,4	9,2	86	4,0
Bi	0,1	0,1	64	2,5	1,2	15,0	1,0	0,4	11,4	88	3,3
Cr	0,3	0,2	58	2,3	0,6	17,6	0,6	0,7	13.0	83	5,2

Tabela 4 Sódio, índice de saturação de sódio (ISNA), boro, enxofre e micronutrientes (Mn, Cu, Zn e Fe)

Horiz.	Na	ISNA	B	S	Mn	Cu	Zn	Fe
	mg dm^{-3}	%	mg dm^{-3}					
A	3,7	0,56	0,3	5,4	4,2	0,4	1,1	83,5
Ab	2,8	0,47	0,2	4,1	0,9	0,2	0,6	26,5
Bi	3,7	0,49	0,1	4,9	0,2	0,1	0,4	31,0
Cr	3,7	0,42	0,1	8,4	2,0	0,1	0,5	6,0

Tabela 5 Ataque sulfúrico, índices Ki e Kr e relação Al_2O_3/ Fe_2O_3.

Horizonte	Ataque sulfúrico					Ki	Kr	Al_2O_3/ Fe_2O_3
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	P_2O_5			
	g kg^{-1}							
A	8,67	7,75	1,62	0,269	0,060	1,90	1,68	7,51
Ab	11,69	10,35	2,13	0,246	0,029	1,92	1,70	7,63
Bi	15,72	12,91	2,43	0,245	0,023	2,07	1,85	8,34
Cr	18,47	15,54	2,54	0,246	0,029	2,02	1,83	9,61

Tabela 6 Curva de retenção de umidade

Horizonte	Curva de retenção de umidade			
	15 atm	0,33 atm	0,10 atm	0,02 atm
	%			
A	95	113	205	356
Ab	90	126	218	325
Bi	104	160	229	360
Cr	120	177	272	364

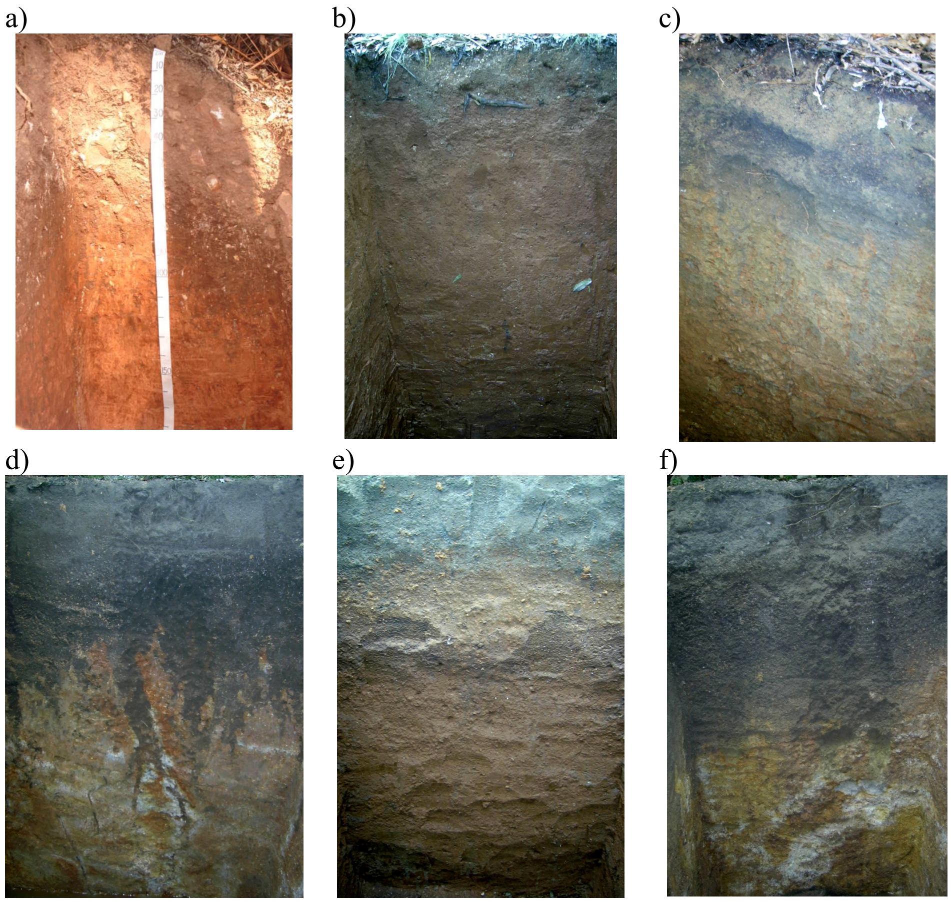

Figura 6 Fotos dos perfis modais descritos nas sub-bacia Terra Dura ,onde a) Perfil MIC 104 PC, b) Perfil MIC 102 TD, c) Perfil MIC 103 TD, e perfis modais descritos na sub-bacia Ponta das Canas, onde d) Perfil MIC 104 PC , e) Perfil MIC 105 PC e f) Perfil MIC 106 PC

CHAPTER 3

Ordinary kriging, regression kriging, and knowledge based inference maps for predicting soil physical properties in Minas Gerais state, Brazil

ABSTRACT

Many of the areas within Brazil lack adequate soil maps which are crucial for proper land management. This study compared the performance of ordinary kriging (OK), regression kriging (RK) and terrain attribute soil mapping (TASM) with fuzzy membership values for predicting soil physical properties in the topsoil (0-15 cm). Mean prediction of error (MPE) and root mean square of prediction error (RMPE) were used for assessing the prediction methods. Two watersheds with contrasting soil-landscape features were studied, where the prediction methods performed differently. Multiple linear stepwise regression model was performed with RK using digital terrain models (DTMs) and remote sensing images. The same DTMs, as well as a classified land use map, were also used in TASM, to the comparison among methods be fair. In most cases, RK and TASM performed better than OK. The knowledge and fuzzy logic used in TASM prediction provided a better estimate for the spatial variability of soil properties for the Marcela Creek Watershed (MCW), where the physical properties seem to follow a systematic patter of distribution, due to pedogenesis. Another reason is the prediction method can be considered as a non-linear transformation of the data. The TASM estimates of soil properties is an adequate accurate option considering: 1) the low correlation or no correlation between DTM and NDVI and physical properties; 2) the high cost of an intense sampling scheme; and 3) the scarce resources for that in Brazil. The data-driven RK usually performed better at Lavrinha Creek Watershed (LCW). Comparing to MCW, higher coefficient of correlation suggests a stronger relationship between contemporary landforms and soil properties, coupled with the fact that more data would be necessary for accounting higher spatial variability at LCW (higher coefficient of variation values of physical properties). Besides the relief and soil, the land use markedly explained the spatial variability of the physical-hydrological properties at both watersheds. It became clearer with prediction maps as well as ANOVA test.

Keywords: Spatial variability. Fuzzy logics. Geostatistics.

1 INTRODUCTION

The estimation of soil physical properties at non-sampled areas can be source of valuable information for land management, water yield, and distributed hydrologic models. Different interpolation techniques, such as geostatistics (e.g. ordinary and universal kriging, regression kriging and others) and fuzzy systems (MCBRATNEY; SANTOS; MINASNY, 2003), have been used, with varying degrees of success, and improved in order to create more accurate soil property maps.

Kriging and its variants have been widely recognized as primary spatial interpolation techniques since the 1970s. It is well documented (ISAAK; SRIVASTAVAS, 1989; JOURNEL; HUIJBREGTS, 1978) and has been used extensively in soil science. The ordinary kriging depends on a weighting scheme dictated by the variogram, where closer sample locations have greater impact on the final prediction (BISHOP; MCBRATNEY, 2001). Nowadays, one advantage of OK is the less complicated to use and it is included in most software packages (HENGL; HEUVELINK; ROSSITER, 2007). As ordinary kriging uses only observed data to map unsampled areas, more recent innovations have been preferred, such as hybrid geostatistical procedures. This technique accounts for environmental correlation, and has become increasingly popular in recent years because they allow utilizing available secondary information and often result in more accurate local predictions (GOOVAERTS, 1999; MCBRATNEY et al., 2000). One example is the regression kriging, in which the interpolation is not only based on observed data, but also regression of the target variable on spatially exhaustive auxiliary variables (HENGL; HEUVELINK; ROSSITER, 2007). Common auxillary variables in soil mapping are digital terrain attributes derived from the DTM and remote sensing images. Regression kriging was used successfully to map soil properties in several landscapes (HENGL;

HEUVELINK; STEIN, 2004; ODEH; MCBRATNEY; CHITTLEBOROUGH, 1995).

Many studies have demonstrated that regression kriging has better performance than ordinary kriging, cokriging or multiple regressions (HERBST; DIEKKRÜ; VEREECKEN, 2006; ODEH; MCBRATNEY; CHITTLEBOROUGH, 1995; SUMFLETH; DUTTMANN, 2008; ZHU; LIN, 2010), depending on the sampling plan adopted. According to Bishop and McBratney (2001), even when only the poorly correlated secondary attributes are available, the hybrid methods may still perform better than the generic geostatistical method of ordinary kriging. Zhu and Lin (2010) investigated the effect of sample size, spatial structure and auxiliary variables for a variety of soil properties, and concluded that when the spatial structure could not be well captured by point-based observations (e.g., when the ratio of sample spacing over correlation range was >0.5), or when a strong relationship existed between target soil properties and auxiliary variables ($R^2 > 0.6$), regression kriging was more accurate for interpolating soil properties. Otherwise, ordinary kriging was better. Simple linear regression modeling is most commonly used to model soil property data. However, the relationship between soil and auxiliary variables is not necessarily linear, and could be unknown and often very noisy (HENGL; HEUVELINK; STEIN, 2004).

Kriging interpolations require the determination of semivariograms and must be calculated with considerable number of points (WEBSTER; OLIVER, 1992) at the appropriate scale. Sample size is one of the most important factors in determining the interpolation accuracy (SCHLOEDER; ZIMMERMAN; JACOBS, 2001), especially in areas with very complex landscapes. Extensive field observations of samples may not always be feasible due to cost and time constraints (ZHU; LIN, 2010). Therefore, kriging methods are best suited for modeling soil spatial variation over small areas (ZHU et al., 2010) and could be considered a data-driven technique.

In Brazil, where areas with extensive field observation are scarce, another quantitative procedure for spatial prediction should be considered. Soil surveys for most of the country are available only at small scale (1:750,000), and just a small portion of the Brazilian territory has semi-detailed or detailed soil surveys, due to funding limitations (GIASSON et al., 2006). One approach that has been used for predicting soil properties and using only one observation per soil class for soil property prediction is TASM (LIBOHOVA, 2010). The premise of this technique is that one or two factors of the five state factors control the distribution of soils on the landscape. When climate, organisms, parent material, and time are relatively constant, the topography would be the greatest driver of soil differentiation. When parent material changes, a new set of new explanatory variables must be developed to define the soil patterns. This method is a rule-based technique where the rules are set within the software based on "if-then" statements. The rules are set based on a centroid or central location where the rules provide 100% probablity of meeting the class. As the auxillary variables get further from meeting all the rules, the probability of the location being in that class changes and alters the soil property prediction. This type of prediction is a fuzzy logic approach to soil property predictions. The number of rules are not limited and information such as land-use derived from remotely sensed date, can be inserted as a rule and the predictions altered based on the land use type.

With this method, terrain attributes such as slope, topographic wetness index, slope, altitude above the channel network and curvature (to name a few) are developed as continuous rasters. The cutoffs are set based on knowledge from a soil scientist who understands the soil-landscape relationship. From the development of this map, continuous rasters are created based on digital terrain models (DTMs) and fuzzy membership values.

The knowledge of pedologists is incorporated into spatial prediction, where the qualitative soil-landscape model is converted to quantitative predictions using relationships between soils and DTMs which provide a relationship between topographical attributes and soil variation. Because TASM requires an understanding of the repeating soil patterns on the landscape from a soil scientist, TASM is considered to be a knowledge based technique. Continuous variation of soils can be represented by continuous soil property maps derived from the similarity vectors (ZHU et al., 1997), and can be viewed as a non-linear transformation of environmental variables based on knowledge of soil-landscape relationships (ZHU et al., 2010).

Landscape features, such as land use, topography, and parent material, are known to control different soil processes and the spatial distribution of soil properties. Thus, the selection of interpolation method can vary between contrasting landscapes, even for the same soil property. In this study, two watersheds located at different geomorphological units were studied, because pedogenesis have strong dependence on geomorphic systems. There are few studies comparing contrasting landscape especially in terms of selecting spatial interpolation methods (ZHU; LIN, 2010). Thereby, the objective of this study was a comparison of OK, RK and TASM for predicting soil physical properties in the State of Minas Gerais, Brazil.

2 MATERIAL AND METHODS

2.1 The study sites

This study was conducted at Marcela Creek Watershed (MCW) and Lavrinha Creek Watershe (LCW) located in Alto Rio Grande Basin, in the State of Minas Gerais, southeast Brazil (Figure 1). The state is divided into Planning Units for Management of Water Resources (UPRGHs). Both watersheds are representative of the Grande River basin, but they are located in different physiographical regions, Mantiqueira Range region (LCW) and Campos das Vertentes region (MCW). These UPRGHs have been extremely important for establishing strategies for development according to the characteristics of the respective watershed (BESKOW et al., 2009). Additional characteristics of study sites are listed in the Table 1.

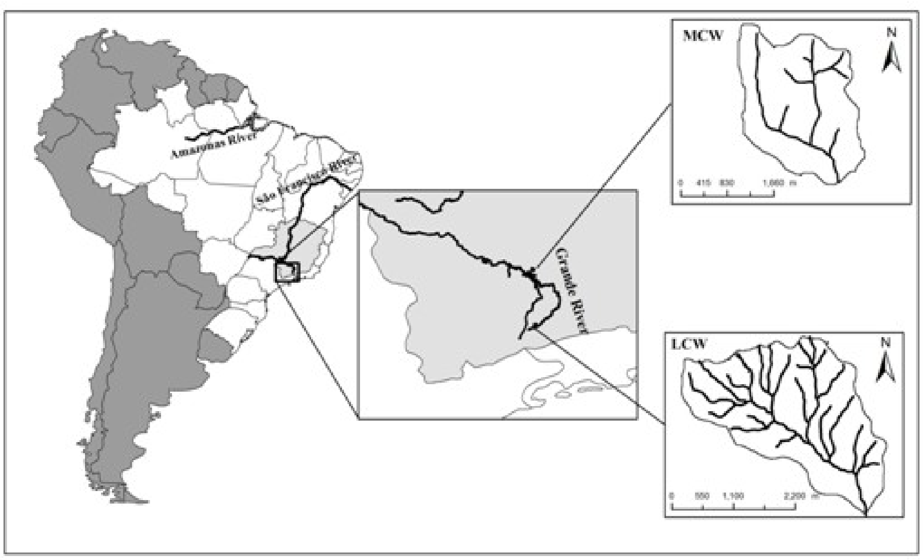

Figure 1 Geographical location of LCW and MCW in Minas Gerais State, Brazil

Table 1 Characteristics of study sites

	Lavrinha Creek Watershed	Marcela Creek Watershed
Location	Between latitudes S 22º6'53" and 22º8'28" and longitudes 44º26'21" and 44º28'39"	Between latitudes S 21º14'27" and 21º15'51" and longitudes 44º30'58" and 44º29'29"
Area	676 ha	470 ha
Elevation	1151 to 1780 m	957 to 1057 m
Mean annual temperature[2]	15°C	19.7°C
Annual Precipitation[3]	2,000 mm	1,300 mm
Native forest	Atlantic Forest (Tropical Rain forest)	Cerrado (Brazilian Savanna)
Land agricultural suitability	Fauna and flora reserve	Crop

[1]Source: Antunes (1986); [2]Source: Geominas (2007)

2.2 Soil sampling and analysis

The topsoil (0-15 cm) was sampled at both watersheds. A total of 198 points were sampled at LCW, following the regular grids 300 x 300 m and refined scale 60 x 60 m and 20 x 20 m, and two transects with the distance of 20 m between points (a total of 54 and 14 sampled points per transect). A total of 165 points were sampled at MCW, following the regular grids 240 x 240 m and refined scale 60 x 60 m. The sampling in refined scale is due the possibility of high spatial variability of physical-hydrical properties at the small scale. In other words, high spatial variability can hamper the variogram structure due to non-stationary of second order for longer distances (infinite variances). Moreover, small scale sampling can reduce the nugget effect, which is related to random errors. The land use and soil classes were criteria used for choosing places with refined scale which would likely correspond to areas where soil properties are likely to change. In order to create one independent validation data set to evaluate the performance of prediction methods, the total data set was divided into interpolation and validation sets. Of the total number of soils sampled, 25 points were used as validation points at LCW and 20 points at MCW. The validation data set was not used in the models to develop predictions.

Soil properties determined were clay content using the pipette method (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA, 1997); bulk density by the volumetric ring method; organic matter according to Walckley and Black (1934); drainable porosity was calculated by the difference between saturation moisture and soil moisture at field capacity (MELLO et al., 2002; QUEIROZ, 1995); saturated hydraulic conductivity (Ksat) were determined *in situ* by constant flow permeameter (Ghelph permeameter - model 2800KI); and total porosity was calculate according to the equation:

$$Total\ porosity\ (\%) = 100 * \left(1 - \frac{bulk\ density}{particle\ density}\right)$$

which particle density was determined by the volumetric flask method (EMBRAPA, 1997).

2.3 Digital Terrain Models (DTMs)

Terrain models were based on a 30 m resolution DEM, generated from counter lines with 1:50.000 scale (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 1973). The sinks were filled and hydrologic consistent DEM was created. The sinks were filled and hydrologic DEM was created. In order to calculate the terrain attributes from DEM, the SAGA GIS 2.0.6 (BÖHNER et al., 2010), ArcGIS spatial analyst (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE - ESRI, 2010) and an extension ArcGIS extension ArcSIE (Soil Inference Engine), version 9.2.402

(SHI, 2011) were used. The following primary -calculated directly from DEM - and secondary - calculated from the combination of two or more primary terrain attributes – DTMs were calculated from DEM:

a) primary: **slope** is the gradient or rate of change of elevation. **Profile curvature** is the direction of the maximum slope and is therefore important for water flow and sediment transport processes. **Plan curvature** is transverse to the slope, which measures the convergence or divergence and hence the concentration of water in a landscape (MOORE et al., 1993);
b) secondary: **altitude above the channel network** (AACHN) describes the vertical distance between each cell of a grid and the elevation of the nearest drainage channel cell connected with the respective grid cell of a DEM. **SAGA wetness index** (WI) was used instead of well known topographic wetness index ($ln(a/tan\beta)$, where a - ratio of upslope contributing area per unit contour length and β - the tangent of the local slope). Both wetness indexes are similar, however, in SAGA is possible the adjustment of the width and convergence of the WI multidirectional flow to single directional flow. Large WI values indicate an increased likelihood of saturated conditions, and are usually found in the lower parts and convergent hollow areas, associated with soils with small hydraulic conductivity or areas of small slope (BEVEN; WOOD, 1983). These indices have been used to identify water flow characteristics in landscape (SUMFLETH; DUTTMAN, 2008).

2.4 Remote sensing data

The normalized vegetation index (NDVI) from LANDSAT satellite image was used for representing organism in Jenny's five factors of soil formation, because the image reflects the biomass status, vegetation type and density. The NDVI is a normalized difference ratio model of the near infrared (NIR) and red bands of multispectral image (NDVI = (NIR band - Red) / (NIR band + Red). The color of high vegetation density (e.g. dense forest) is white; areas in gray shades representing intermediate vegetation density, with darker gray areas having lower vegetation cover and lighter gray areas having higher vegetation cover (BOETTINGER, 2010; BOETTINGER et al., 2008).

2.5 Ordinary and regression kriging

The first step in ordinary kriging is to calculate the experimental semivariogram using the following equation:

$$\gamma^*(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

where $\gamma^*(h)$ is the estimated value of the semivariance for lag h; $N(h)$ is the number of experimental pairs separated by vector h; $z(x_i)$ and $z(x_i+h)$ are values of variable z at x_i and x_i+h, respectively; xi and x_i+h are position in two dimensions. Experimental semivariograms were fitted with spherical, exponential and gaussian and the adjustments Maximum Likelihood (ML), Ordinary Least Square (OLS) and Weight Least Squares (WLS) were also applied. The best OK model and its adjustments were evaluated using cross-validation (leave-one-out). The models with lower average error and standard deviance of error closer to 1 were chosen.

The regression kriging combines multiple linear regression and ordinary kriging (BISHOP; MCBRATNEY, 2001; HENGL; HEUVELINK; ROSSITER, 2007; ZHU; LIN, 2010). Firstly, stepwise multiple linear regressions technique of target variable using predictive ancillary variables were carried out in order to model the trend component. The predictive input variables of models were altitude, slope, WI, plan curvature, profile curvature and NDVI were used at LCW. At MCW the AACHN, slope, plan curvature, profile curvature and WI were used. In the second regression kriging step, ordinary kriging is applied to the residuals of multiple regressions and a spatial prediction of the residuals was created. The final maps were an additive combination of both models in a regression kriging approach. The normal distribution is an ideal requirement for linear regression (DRAPER; SMITH, 1998). Thus, the non-normal distributed data were log transformed. The kriging and statistical analysis were carried out in statistical software R (R DEVELOPMENT CORE TEAM, 2010).

2.6 TASM

This method allows creating raster based continuous soil properties, based on terrain attributes soil mapping (TASM) and fuzzy membership values, using expert knowledge and field samples. Initially, the soil-landscape relationships were established using analog and digital sources. Except for NDVI image, the terrain attributes used in TASM maps were also applied in RK to provide a fair comparison among methods. However, the property maps were based on soil landscape relationships and threshold values were identified and assigned to each soil mapping unit. The soils were classified according to Brazilian soil classification system (EMBRAPA, 2006).

LCW is a headwater watershed located at Mantiqueira Range Region. The parent material is gneiss from Neoproterozoic, whose alteration resulted in predominance of Cambisols (moderately developed and well drained soil classes). The relief is steep with concave-convex hillside, predominance of linear pedoform, and narrow fluvial plains (CENTRO TECNOLÓGICO DE MINAS GERAIS - CETEC, 1983; RADAMBRASIL, 1983). Hydromorphic soils occupy the toeslope position, where the water table is near to the surface most of the year.

MCW is located at Campos das Vertentes Plateau geomorphological unit, where the dissection pattern is homogenous (CETEC, 1983; RADAMBRASIL, 1983). The parent material is micachist and phyllite from Proterozoic. The relief is represented by gentle slopes with intense soil development, where Latosols are the most expressive soil classes. Considering the relationship of soils and their environments (JENNY, 1941), the Latosols were formed on stable and very old surfaces conducive to intense weathering-leaching under warm and moisty climate, where organisms were very active. Together, the individual factors contribute to the formation of highly weathered tropical soils (MOTTA; CURI; FRANZMEIER, 2002). Latosols are associated with Cambisols (GIAROLA et al., 1997) that occupy the more dissected positions (MOTTA et al., 2001), and more linear portions inside a convex macropedoform on the landscape. Hydromorphic soils occupy the youngest surface on the toeslope positions.

Red Latosols (2.5YR or redder) generally occupy flatter and convex summit positions. The Yellow (7.5YR or yellower) and Red-Yellow (less redder than 2.5YR and redder than 7.5YR) Latosols occupy landscape positions from the summit to footslope positions. These colors show a preterit hydrological influence, where the type of orientation of parent material layers, by conditioning a different moisture regime in two systems exerted influence on the pedogenesis of the Red, Yellow and Red-Yellow Latosols. The horizontal orientation of the layers conditioned the genesis of the Yellow and Red Yellow

Latosols, having higher goethite/hematite proportion and consequent yellowish colors, as a result of moister soil conditions than in redder soils (CHAGAS et al., 1997). The inclined orientation of the layers conditioned under similar conditions, the formation of Red Latosols having better drainage and higher weathering-leaching, higher hematite/goethite proportion and, consequently, reddish colors. Due the current climate conditions, the soils are well drained. The present pedogenetic environment is favoring kaolinite sand gibbisite stabilization and goethite formation, removing hematite and being probably responsible for the yellowing (xanthization) of superficial horizons (DUARTE et al., 2000; MOTTA; CURI; FRANZMEIER, 2002).

The relationships between soil and terrain attributes were quantified using DTMs and membership functions on ArcSIE. Analogous to a DEM, a DTM is an ordered array of numbers that represent the spatial distribution of terrain attributes across a landscape in a raster-based format (BISHOP; MINASNY, 2005). The knowledge about the soil-landscape relationships can be qualitatively modeled using DTM, since the terrain attributes represent soil and hydrological processes. Thus, a qualitative soil landscape model cited above was used to quantify soil-landscape relationships on a continuous basis, based on different terrain attributes and their ranges. The rules were set based on soil scientist' knowledge, maps from previous soil survey (MENEZES et al., 2009; MOTTA et al., 2001) and other types of soil research developed in the study sites (CHAGAS et al., 1997).

At LCW, higher values of WI and low slopes were used for mapping hydromorphic soils in flatter alluvial areas (footslope). The Inceptisol occupies the well drained portions of landscape with lower values of WI (summit, shoulder, backslope), formed by different combinations and ranges of slope, plan and profile curvature. The environmental control variables and their ranges are presented in Table 2.

At MCW, the Red Latosol occupy the flatter summit positions in a more convex pedoform, expressed by higher values of AACHN, lower values of slope and negative values of plan curvature. The Yellow and Red-Yellow Latosols are present on the shoulder, backslope and footslope positions (intermediate values of AACHN and gentle slopes). Two instances were applied for Inceptisol: one considering steeper slopes, and another one for plan and profile curvatures. These instances were integrated using multiplication of functions. Hydromorphic soils (Haplic Gleisols) are located in lower AACHN and higher values of WI. The ranges of environmental variables are presented in Table 3. The ArcSIE interface, as well as the shape of curves was described by McKay et al. (2010).

Table 2 Environmental control variables of soil classes at LCW

Soil type[1]	Full membership				
	Altitude	Slope	WI	Plan curvature	Profile curvature
FN	1156	1	15-21	-	-
HC1	-	32.5	7	1	2.3
HC2	-	15	7	-1	0
HC3	-	32.5	7	-1	0
HC4	-	51	7	-1	0
	50% membership				
FN	1200	10	14,22	-	-
HC1	-	19.5,45.5	0,14	0.11.3	1.56,9.5
HC2	-	10,20	0,14	-11,0	-1.5,1.5
HC3	-	19.5,45.5	0,14	-11,0	-1.5,1.5
HC4	-	45-95	0,14	-11,0	-1.5,1.5
	Curve shape				
FN	Z	Z	Bell	-	-
HC1	-	Bell	Bell	Bell	Bell
HC2	-	Bell	Bell	Bell	Bell
HC3	-	Bell	Bell	Bell	Bell
HC4	-	Bell	Bell	Bell	Bell

[1]FN – Fluvic Neosol; HC – Haplic Cambisol

Table 3 Environmental control variables of soil classes at MCW

Soil type[1]	Full membership				
	AACHN	Slope	WI	Plan curvature	Profile curvature
GX	0.1	-	15.5	-	-
RL	23.53	2.7	-	-0.9	-
HC	4	30	-	-1	-1.75
YL	5	5.5	-	-	-
RYL	5	14	-	-	-
			50% membership		
GX	1.5	-	14.5,19	-	-
RL	20,56	0,10	-	-4.3,0	-
HC	2,23	20	-	-2.3,-1.1	-4.35,-0.75
YL	2,15	3,8	-	-	-
RYL	2,23	8,20	-	-	-
			Curve shape		
GX	Z	-	Bell	Bell	-
RL	Bell	Bell	-	-	-
HC	Bell	S	-	-	Bell
YL	Bell	Bell	-	-	-
RYL	Bell	Bell	-	-	-

[1]HG – Haplic Gleisol; RL – Red Latosol; HC – Haplic Cambisol; YL – Yellow Latosol; RYL – Red-Yellow Latosol

The terrain attribute values and ranges associated with each soil map class were used to define membership functions. ArcSIE, designed for creating soil maps under fuzzy logic, supports the knowledge based approach to establishing the relationships between soil and its environment, providing tools for soil scientists to formalize the relationship based on pedological knowledge of the local soils. The membership functions referred to as optimality functions as they define the relationship between the values of an environmental feature and soil type. The Rule-Based Reasoning (RBR) inference was used to define the relationship between values of an environmental variable and a given soil class (SHI, 2011).

The soil-landscape relationships were extracted, and the characterized environmental conditions were linked through a set of inference techniques to populate the similarity model for a given area (ZHU; MCKAY, 2001). Thus, the continuous variation of soils can be represented by continuous soil property maps derived from the similarity vectors, using the following formula (ZHU et al., 1997):

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

where V_{ij} is the estimated soil property value at location *(i,j)*, V^{k} is the typical value of a given soil property (e.g. clay content) of soil class *k* (e.g. Haplic Cambisol), and *n* is the total number of prescribed soil classes for the area. If the local soil formative environment characterized by a GIS resembles the environment of a given soil category, then property values of the local soil should resemble the property values of the candidate soil type. The resemblance between the environment for soil at (*i,j*) and the environment for soil category *k* is expressed as S_{ij}^{k}, which is used as an index to measure the level of resemblance between the soil property values of the local soil and those of soil category (ZHU et al., 2001).

The higher the membership of a local soil in a given soil class the closer the property values at that location will be to the typical property values of the series (ZHU et al., 2010). Two different criteria were used for choosing representative values (V^k): the mean of values within soil type polygon (defuzzified map or hardened) and the property value sampled at a field location where the fuzzy membership of the local soil to the given soil type, is the highest among all sampled points. In other words, the property value was chosen when it is at most representative position in the landscape.

Different land uses were also considered in the prediction. Landsat images were classified with support of field observations, and polygons with same land use were created. In ArcSIE, land use raster maps were used as categorical data (data do not have quantitative meaning, values are only for labeling or categorizing different land uses) and overlaid with all soil classes, using the function type Nominal (SHI, 2011). In order to assess if the physical property is significantly influenced by different types of land use, analysis of variance (ANOVA) were made by F test ($p<0.01$ or $p<0.05$). The land uses at LCW are native forest (Atlantic Forest), natural regeneration, pasture and wetland, and at MCW land uses are native forest (Brazilian Savanna), pasture, maize and eucalyptus. According to the silimilarity vector formula, the typical value V^k came from the combination of soil and land use *k,* e.g. Haplic Cambisol under pasture.

The box-cox procedure (BOX; HUNTER; HUNTER, 1978) was carried out to determine the suitable type of transformation for ANOVA. Drainable porosity, total porosity (at LCW) and Ksat (at MCW) were log transformed. The statistical analyses were performed in SAS version 9.2 (STATISTICAL ANALYSIS SYSTEM INSTITUTE - SAS INSTITUTE, 2008).

2.7 Comparison of methods

The prediction methods assume different structures of the data and in this sense, they are not equivalent. Therefore, only a validation data set, which was not used for prediction, was used to assess the best prediction method (HENGL; HEUVELINK; STEIN, 2004; ODEH; MCBRATNEY; CHTTLEBOROUGH, 1994; VOLTZ; WEBSTER, 1990). Two indices were calculated from the observed and predicted values. The mean prediction of error (MPE) was calculated by comparing estimated values ($\hat{z}\left(s_j\right)$) with the validation points ($z^*\left(s_j\right)$):

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

and the root mean square prediction error (RMSPE):

where *l* is the number of validation points. The MPE measures the bias of prediction, and RMSE measures the precision of prediction. The relative improvement (RI) of RK and TASM over OK was assessed by using RMSPE:

$$\text{RI} = \frac{RMSPE_{ok} - RMSPE_{best\ method}}{RMSPE_{ok}} * 100$$

3 RESULTS AND DISCUSSIONS

3.1 Descriptive statistics

The descriptive statistics in Table 1 show the different variations of the physical properties. The interpolation and validation data sets were representative and appropriate because they showed similar statistical characteristics with the full data set. As a general trend, LCW has the higher values of organic matter due the combination of type of native forest (rain forest), colder climate and current land use (41.5% native forest, 13.2% natural regeneration, 40.4% pasture, and 4.9% wet land). Particularly at surface layers, the intense faunal activity and high root density added to higher organic matter content, reflected on lower values of bulk density, and higher values of total porosity, drainable porosity and Ksat (MENEZES et al., 2009), when compared to MCW. Soils at that watershed are less weathered (predominance of Inceptisols) and have lower clay content. The CV values are relatively higher denoting larger spatial variability, in accordance with its younger and less stable soils.

The environmental conditions at MCW demonstrated lower organic matter content, because the carbon oxidizes more readily under warmer climate and lower rainfall, and due to the type of current land use (72.7% pasture, 17.4% maize, 6.9% native forest and 3% eucalyptus). The clay content was noticeably higher in the MCW when compared to the LCW. It is well known that Latosols have good physical properties with strong aggregate stability (FERREIRA; FERNANDES; CURI, 1999). However, this phenomenon is usually better expressed in the B horizon. The soil physical properties in the topsoil are more influenced by land use than other factors. MCW showed general trend of lower CV values, indicating smaller spatial variability, except for Ksat, whose values were the highest among the physical properties at both watersheds. These findings are in agreement with its older and more stable soils.

Table 4 Descriptive statistics for soil physical-hydrological properties

Soil property	Data set	LCW						MCW					
		Mean	Median	STD	CV	Min	Max	Mean	Median	STD	CV	Min	Max
Clay (%)	Full	30	30	6.45	22	12	51	60	60	8.29	13	25	82
	Interpolation*	30	30	6.38	21	12	51	60	61	7.89	13	32	82
	Validation**	28	29	6.78	24	14	49	56	58	10.2	18	25	73
Organic matter (%)	Full data	4.8	4.6	2.25	46	1.9	12.9	2.9	3	0.93	33	1.1	5.3
	Interpolation	4.6	4.3	2.12	46	1.9	12.9	2.9	3.1	0.92	32	1.4	5.3
	Validation	6.5	6	2.42	37	3.4	12.9	2.2	2	0.75	33	1.1	3.7
Bulk density (g dm^{-3})	Full	1.00	1.01	0.21	21	0.58	1.45	1.12	1.12	0.10	9	0.82	1.32
	Interpolation	0.97	1.01	0.21	21	0.58	1.4	1.12	1.12	0.09	8	0.82	1.32
	Validation	1.01	1.04	0.23	22	0.65	1.45	1.13	1.17	0.11	1	0.96	1.31
Total porosity (%)	Full	59	59	7.87	13	44	76	56	56	4.32	7	42	67
	Interpolation	59	59	7.8	13	45	76	56	56	4.36	7	42	68
	Validation	58	57	8.17	14	44	72	55	55	3.96	7	47	61
Drainable porosity (%)	Full data	27	25	11.43	42	6	53	15	14	6.57	43	4	32
	Interpolation	27	26	11.4	42	6	53	15	14	6.46	42	4	32
	Validation	25	24	11.44	45	8	50	14	14	7.29	50	4	30
Ksat (m day^{-1})	Full	1.65	0.95	3.02	183	0	32.35	0.8	0.46	0.93	117	0.03	6.99
	Interpolation	1.65	1.02	2.98	180	0	32.35	0.81	0.48	0.97	118	0.03	6.99
	Validation	1.64	0.18	3.27	199	0	16.00	0.68	0.43	0.59	87	0.08	1.91

Interpolation: data sets used for modeling. ** Validation: data sets used exclusively for valitadion. Min: minimum; max: maximum; STD: standard deviation; CV: coefficient of variation (%)

3.2 Ordinary kriging and Regression Kriging

Properties highly variable make more difficult to get a reasonable estimate of the variogram (ARMSTRONG, 1984). The abnormally large or small values, also called outliers, can be assessed by histograms. Since the frequency distribution of Ksat is highly skewed (Figure 2a, 2b), the data were log transformed, in agreement with the general thinking that the measurements of many natural phenomena tend to have a lognormal distribution (ALVARENGA, 2010; MOUSTAFA, 2000). The variogram of the target data-transformed (Figure 2e and 2f) yielded a better interpretable spatial structure than non-transformed data (Figure 2c and 2d). The transformation of target data set was not necessary for the other soil physical attributes for OK analysis.

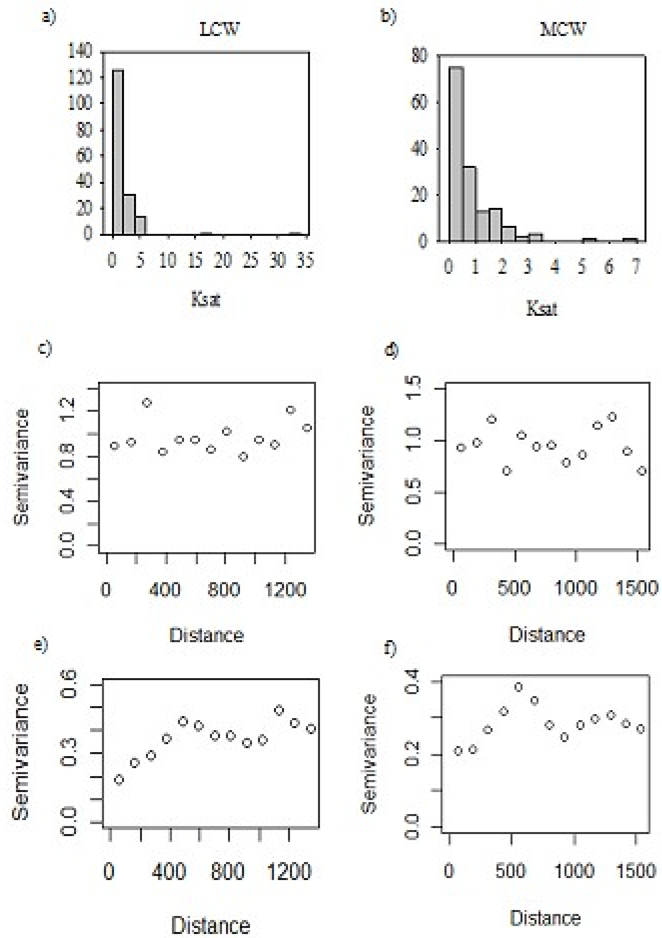

Figure 2 Histograms (a and b), empirical variograms of Ksat non-transformed (c and d) and log-transformed (e and f)

The parameters used to fit semivariograms of target (OK) and residuals of multiple linear regression are presented in Table 5 and 6, and semivariograms presented in Figures 3 and 4. Better adjustments of target variables through OLS methodology were found at LCW, with the exception of clay content (WLS). The three adjustments (WLS, OLS, and ML) performed similarly at MCW. In general, the variograms of targets and residuals have approximately the same form and nugget, but the residual variogram has a somewhat smaller sill and range, in agreement with Hengl, Heuvelink and Rossiter (2007) and Hengel, Heuvelink and Stein (2004).

Table 5 Geostatistical parameters for the best-fitted semivariograms of the target variables and the residuals of multiple linear regression at LCW

Soil property	Model	Target			Residuals			Nugget/sill[1]	Strength of spatial structure[2]
		Range (m)	Sill - Nugget	Nugget	Range (m)	Sill - Nugget	Nugget		
		LCW							
Clay (%)	Exponential WLS	148.09	12.13	20.63	91.73	10.32	20.63	1.70	Weak
Organic matter (%)	Gaussian OLS	763.98	5.86	0.51	763.98	3.36	1.27	0.09	Strong
Bulk Density (g dm^{-3})	Exponential OLS	623.63	0.06	0	374.19	0.029	0.012	0.00	Strong
Total porosity (%)	Exponential OLS	584.64	81.21	0	454.71	53.86	9.62	0.00	Strong
Drainable porosity (%)	Gaussian OLS	618.37	144.26	36.07	701.57	117.82	45.31	0.25	Medium
logKsat (m day^{-1})	Exponential OLS	436.5	0.33	0.15	218.27	0.24	0.15	0.45	Medium

[1]Calculated from the target data set.[2] Values <0.25 being strong, 0.25-0.75 being medium, and >0.75 being weak (CAMBARDELLA et al., 1994)

Tabela 6 Geostatistical parameters for the best-fitted semivariograms of the target variables and the residuals of multiple linear regression at MCW

Soil property	Model	Target			Residuals			Nugget/sill[1]	Strength of spatial structure[2]
		Range (m)	Sill - Nugget	Nugget	Range (m)	Sill - Nugget	Nugget		
					LCW				
Clay (%)	Exponential ML	285.81	27.35	32.82	171.49	26.13	30.13	1.20	Weak
Organic matter (%)	Gaussian WLS	311.80	0.52	0.39	279.6	0.49	0.39	0.75	Weak
Bulk Density (g dm^{-3})	Spherical ML	571.60	0.0044	0.0058	714.5	0.0038	0.0058	1.32	Weak
Total porosity (%)	Exponential OLS	817.00	14.06	12.14	545.68	11.22	11.22	0.86	Weak
Drainable porosity (%)	Gaussian OLS	36.38	29.50	11.78	36.38	28.10	11.78	0.39	Medium
logKsat (m day^{-1})	Gaussian WLS	332.60	0.11	0.20	291.04	0.09	0.21	1.82	Weak

[1]Calculated from the target data set.[2] Values <0.25 being strong, 0.25-0.75 being medium, and >0.75 being weak (CAMBARDELLA et al., 1994)

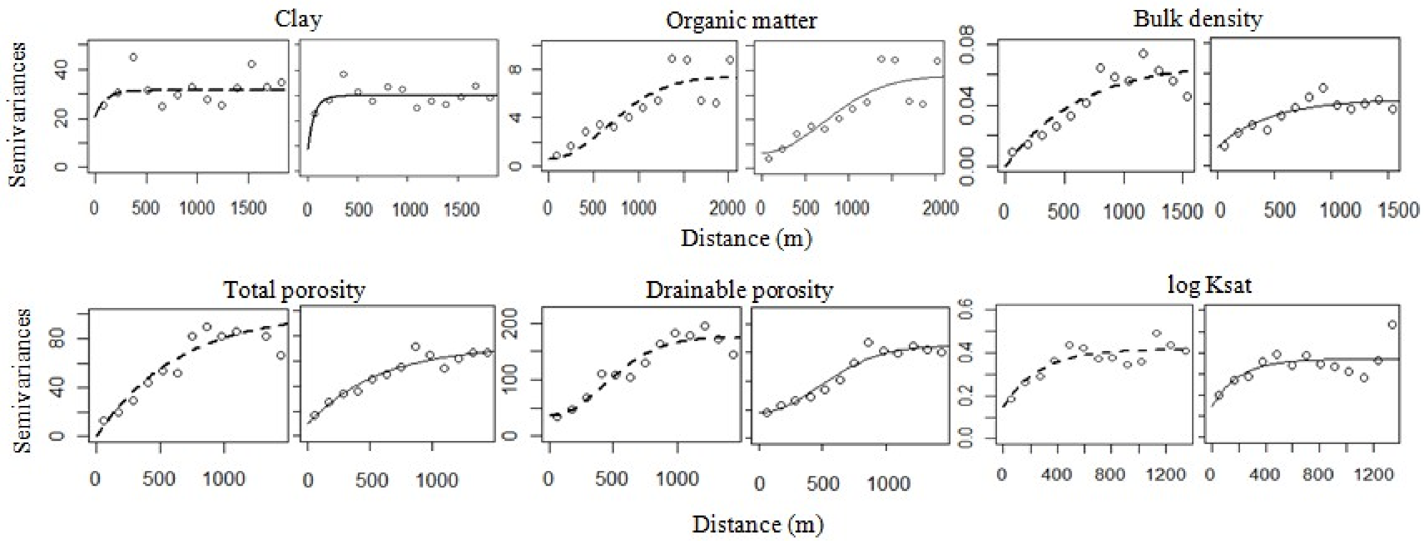

Figure 3 Semivariograms of target variable (dotted line) and the residuals of linear regression (right side) at LCW

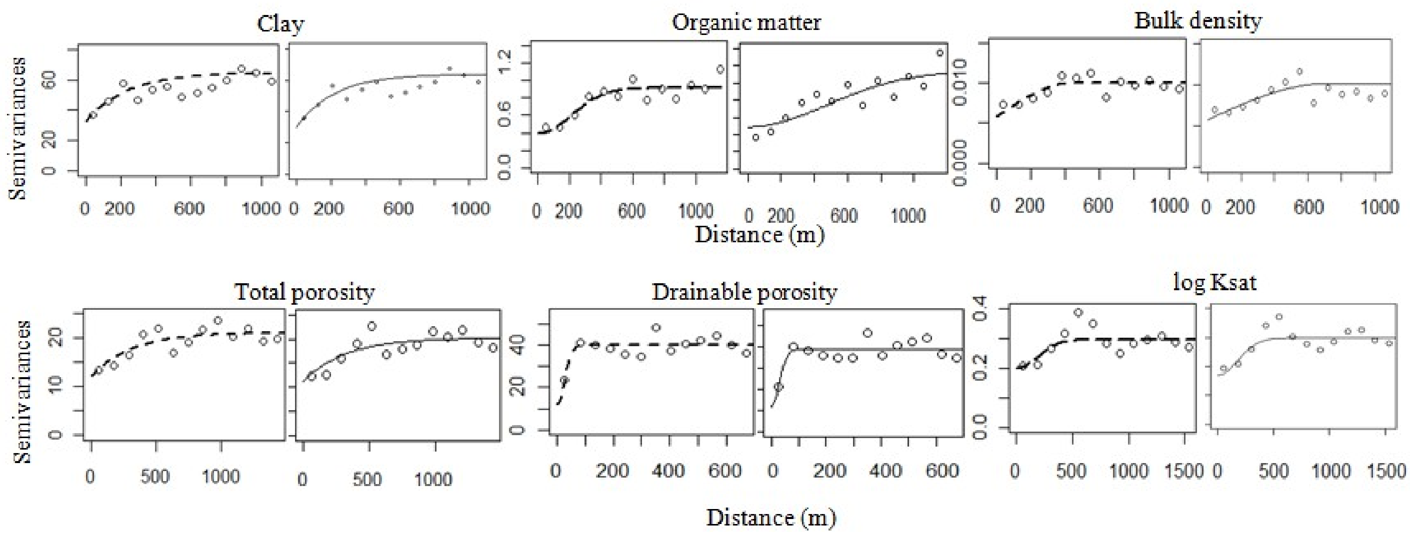

Figure 4 Semivariograms of target variable (dotted line) and the residuals of linear regression (right side) at MCW

Table 7 Stepwise multiple linear regression models between soil physical properties and covariates attributes at LCW

Soil Properties	Altitude	Slope	WI	Plan curvature	Profile curvature	NDVI	R^2
Clay (%)	-	-	-	-	-0.9077	-	0.07
Organic matter (%)	0.010129	-	-	-0.115689	0.211202	4.734977	0.22
Bulk Density (g dm^{-3})	-0.0010016	0.0028765	-	-	-0.0371671	-	0.20
Total porosity (%)	0.03702	-0.16296	-1.07596	0.48210	1.46226	-	0.19
Drainable porosity (%)	0.050071	-0.142373	-	-	-	-	0.15
Ksat (m day^{-1})	0.0039241	-	-	-	-	-	0.30

Table 8 Stepwise multiple linear regressions between soil physical properties and covariates attributes at MCW

Soil Properties	AACHN	Slope	WI	Plan curvature	Profile curvature	NDVI	R^2
Clay (%)	-	-0.1626	-	-	-	17.0480	0.06
Organic matter (%)	0.012492	-	-	-	-	-	0.05
Bulk Density (g dm^{-3})	-0.0010715	-	-0.0226413	-	-0.0141589	-	0.12
Total porosity (%)	0.06602	-	0.95371	-	0.71823	-	0.12
Drainable porosity (%)	-	-0.13880	-	0.89071	-	-	0.05
Ksat (m day^{-1})	0.006330	-	-	-	-	-	0.04

Variograms have been used to describe and measure the spatial structure of spatial data sets. Nugget over sill ratio (N/S), which defines the proportion of short-range variability that cannot be discribed by a geostatistical model based on a variogram, has been used to quantify the strenght of spatial structure. An N/S ratio of 0.09 means that 9% of the variability consistis of unexplainable or random variation. Apart from random factors, structural factors, such as the parent material, terrain, and soil characteristics (e.g. texture, mineralogy and pedogenic processes) can codetermine the soil properties. LCW showed stronger strength of spatial structure than MCW. And also, as long as the nugget effect is high, there may be undesirable large estimates of variances, providing less smoother and reliable OK maps (MOUSTAFA, 2000). There was no direct relationship between CV and the strength of spatial prediction (N/S). LCW showed higher CV and lower values of nugget/sill and nugget effect as well. The opposite situation occurred in the MCW, in disagreement with Utset, López and Díaz (2000).

Since the relief parameters control water and sediment distributions over the landscape, terrain attributes are correlated with soil physical properties. These dependencies were detected by stepwise multiple linear regression models (Table 7 and 8). The Akaike-information criterion (AIC) (AKAIKE, 1973) was used to decide if an independent covariate was kept in the regression or not, as well as avoids spurious details in the prediction map (HENGL; HEUVELINK; ROSSITER, 2007). The altitude and AACHN were some of the best predictors at LCW and MCW, respectively. These DTMs are related to different patterns of soil wetness, sediment movement (SCHAETZL; ANDERSON, 2005), and land use, which in turn influence organic matter distribution.

Considering the factors of soil formation (JENNY, 1941), the NDVI was used to approximate the organism in terms of generalized land cover and land use (MALONE et al., 2009). This index has shown to correlate well with the distribution of organic matter (MALONE et al., 2009; MENDONÇA-SANTOS et al., 2010; ZHAO; SHI, 2010), which in turn could influence soil physical properties. However, NDVI was only significantly correlated with organic matter at LCW. For those soil properties that were not correlated with NDVI, considering the five soil formation factors, only the relief was used to take account of spatial variability in the regression.

The coefficient of determination (R^2) is the proportion of variability of interpolation data set that is accounted for by the statistical model. However, the multiple linear regression is one step of RK. A key issue is whether the correlations could be used to improve the prediction performance. In comparison of MCW, the correlations at LCW could be considered better, whose values of R^2 varied from 0.15 to 0.30. The clay content was the exception (R^2=0.07), and showed less agreement. The poor relationship to clay content may be explained by the physical process. The steep slopes at LCW may contribute to the erratic distribution because of the differential erosion which could result in a low correlation between terrain and soil property.

At MCW the predictors included in the model did not explain the variance of four physical properties, whose R^2 values were less than 0.06. The reason may be due to the complexity of the relationship between environmental and soil variables. These relationships may be complex, unknown, often very noisy, and is not necessary linear, as assumed by the multiple regression (HENGL; HEUVELINK; STEIN, 2004; MCKENZIE; RYAN, 1999). According to Herbst, Diekkrü and Vereecken (2006), the spatial variability of soil properties is complex, and sometimes so complex that only parts of the spatial structure can be described in a deterministic way. And also, other sources of variation related to pedogenesis or land use might be responsible for the distribution of physical properties across the landscape. The steep relief at LCW, with predominance of erosional surfaces, where mostly Inceptisols are formed and sediments have been deposited, suggest a stronger relationship between contemporaneous landforms and soil properties.

3.3 Anova test for TASM prediction

ANOVA test (Tables 9 and 10) was employed to support the decision about using the land use as categorical information in TASM. The variance between land uses was statistically significant, which means the land use affected physical properties, with the exception of Ksat in the MCW. The values of Ksat encompass not only the topsoil properties, and therefore, it might be influenced by deeper pedological features more than the surface land use features. Soils at this watershed are mainly Latosols, whose structure helps to explain the variability pattern. The good physical properties of Latosols are mainly influenced by their high aggregate stability. Micro-aggregates of clay (largely kaolinite and gibbsite) are stabilized by considerable contents of Al- and Fe-oxides (VITORINO et al., 2003), organic matter, or both. According to Ajayi et al. (2009) and Resende et al. (2007) the aggregate stability is primarily influenced by the oxidic fraction. Hydraulic conductivity can be defined as a measure of the ability of a soil to transmit water. Due to strong aggregate stability, the water moves through these Latosols readily (MOTTA; CURI; FRANZMEIER, 2002). Therefore, there should be a strong relationship between aggregate stability and hydraulic conductivity.

Summary statistics of soil physical properties for the data stratified into four land uses are listed in Table 11. Different types of land use were joined or treated separately, based on mean test for separation. For example, the organic matter mean test at MCW showed that native forest is statistically different from the other land uses. Thus, the raster map was reclassified into two different nominal categories for each soil class with crisp boundaries: one nominal value for native forest, and another nominal value for natural regeneration, pasture and wetland. Thus, a soil type was created by the combination of soil and land use. However, the issue here is whether the categorical land use maps can in fact improve the accuracy of prediction of physical properties.

Table 9 Summary of ANOVA performed to test the significance of land use effects on the variance of soil properties at LCW

Soil property	Source of variance	df	Sum of squares	Mean square	F value
Clay (%)	Land use effect	3	606.658801	202.219600	5.10**
	Residual	188	7570.028378	39.633656	
Organic matter (%)	Land use effect	3	149.1740448	49.7246816	11.34**
	Residual	188	842.1146797	4.3860140	
Bulk density (g cm^{-3})	Land use effect	3	2.74024666	0.91341555	29.44**
	Residual	188	5.83378459	0.03103077	
Total porosity (%)	Land use effect	3	0.20351030	0.06783677	28.62**
	Residual	188	0.44558511	0.00237013	
Drainable porosity (mm)	Land use effect	3	2.51321415	0.83773805	28.51**
	Residual	187	5.49527611	0.02938650	
Hydraulic conductivity saturated (m day^{-1})	Land use effect	3	97.437301	32.479100	3.67**
	Residual	192	1696.962386	8.838346	

* Significant at the 0.05 level. ** Significant at the 0.01 level

Table 10 Summary of ANOVA performed to test the significance of land use effects on the variance of soil properties at MCW.

Soil property	Source of variance	df	Sum of squares	Mean square	F value
Clay (%)	Land use effect	3	1597.10366	532.36789	8.80**
	Residual	158	9560.70498	60.51079	
Organic matter (%)	Land use effect	3	11.5284157	3.8428052	4.74**
	Residual	158	128.0081892	0.8101784	
Bulk density (g cm^{-3})	Land use effect	3	0.08183827	0.02727942	2.72*
	Residual	158	1.58182947	0.01001158	
Total porosity (%)	Land use effect	3	209.818465	69.939488	3.87*
	Residual	158	2858.115947	18.089341	
Drainable porosity (mm)	Land use effect	3	578.732232	192.910744	4.69**
	Residual	158	6496.188032	41.115114	
Ksat (m day^{-1})	Land use effect	3	0.82612445	0.27537482	1.03
	Residual	1158	42.18503751	0.26699391	

* Significant at the 0.05 level. ** Significant at the 0.01 level

Table 11 Statistics of soil physical properties at LCW and MCW

Land use[1]	Clay (%)		Organic matter (%)		Bulk density (g dm^{-3})		Total porosity (%)		Drainable porosity (%)		K sat (m day^{-1})	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD	Mean	STD
LCW												
NF	29.50b	6.04	5.96a	2.13	0.86b	0.20	64,59a	0.06	33.11a	1.52	2.53a	4.15
NR	31.93a	5.95	4.33b	1.86	1.06a	0.15	54,54b	0.04	24.48b	1.38	0.98b	0.94
P	29.96a	6.77	4.14b	2.19	1.12a	0.17	57,47c	0.05	18.33c	1.51	1.20b	2.32
WL	23.00c	5.81	3.77b	1.98	0.99a	0.14	58,86b	0.03	17.70bc	1.36	0.76ab	0.76
MCW												
NF	58.00b	11.78	2.68a	0.87	1.14b	0.10	54.76b	4.80	13.36b	7.51	0.31a	2.87
P	56.65b	7.65	2.74a	0.88	1.13b	0.09	55.12b	4.01	14.44b	6.31	0.41a	3.33
C	57.10b	6.59	2.96a	0.99	1.08a	0.12	57.75a	4.92	18.75a	6.19	0.48a	3.47
E	69.07a	7.50	3.65b	0.82	1.10b	0.10	56.65b	3.51	14.10b	6.71	0.64a	2.81

[1]Land use: NF – native forest; NR –natural regeneration; P – pasture; WL – wetland; C – maize; E – eucalyptus. [3]STD – standard deviation. Means followed by the same letter do not differ significantly ($p<0.05$)

3.4 Assessment of prediction methods

The comparison of prediction methods are showed in Table 12. The best prediction methods for each soil property showed the smallest MPE and RMSPE. On general, the biases of OK and RK were lower than the bias of the TASM method.

Table 12 Comparison of interpolation methods and relative improvement at LCW

		Clay	Organic Matter	Bulk density	Total porosity	Drainable porosity	Ksat
OK	MPE	0.779	-0.663	0.009	-0.312	-1.461	0.439
	RMSPE	3.897	3.317	0.045	1.562	7.305	2.196
RK	MPE	0.966	-0.482	0.002	-0.212	-1.460	0.242
	RMSPE	4.831	2.408	0.012	1.462	7.301	1.208
TASMMean	MPE	1.731	-2.002	-0.112	1.868	1.610	0.385
	RMSPE	8.656	10.009	0.559	9.338	8.050	1.932
TASMMeanLU	MPE	1.205	-1.950	00.024	1.070	2.401	0.387
	RMSPE	6.026	9.752	0.120	5.352	12.006	1.933
TASMLandscape	MPE	-1.562	-1.809	0.125	-1.814	-5.835	0.257
	RMSPE	7.811	9.044	0.624	9.070	29.174	1.283
TASMLandscapeLU	MPE	2.371	-1.113	0.058	-1.550	-0.399	0.299
	RMSPE	11.854	5.565	0.290	7.750	1.993	1.147
RI (%)		-24	27	73	6	72	48

OK – ordinary kriging; RK – regression kriging; TASMMean: terrain attributes soil mapping using mean as a representative value without land use; TASMMeanLU: terrain attributes soil mapping using mean as a representative value with land use; TASMLandscape: terrain attributes soil mapping using landscape position as a representative value without land use; TASMLLU: terrain attributes soil mapping using landscape position as a representative value with land use MPE: mean prediction of error; RMSPE: root mean square of prediction error; RI: relative improvement

Table 13 Comparison of interpolation methods and relative improvement at MCW

		Clay	Organic Matter	Bulk density	Total porosity	Drainable porosity	Ksat
OK	MPE	1.977	0.146	-0.005	0.056	0.936	0.087
	RMSPE	8.842	0.659	0.063	0.250	4.188	0.368
RK	MPE	-	-	-0.015	0.517	-	-
	RMSPE	-	-	-0.023	2.312	-	-
TASMMean	MPE	3.697	0.627	-0.003	0.500	0.543	-0.013
	RMSPE	16.535	2.803	0.012	2.238	2.428	0.057
TASMMeanLU	MPE	2.625	0.533	-0.018	0.460	1.257	-
	RMSPE	11.740	2.383	0.079	2.058	5.622	-
TASMLandscape	MPE	-1.527	0.277	-0.005	0.448	-3.592	0.442
	RMSPE	6.831	1.237	0.022	2.002	16.066	1.876
TASMLandscapeLU	MPE	2.535	0.140	-0.016	0.657	-1.349	-
	RMSPE	11.339	0.653	0.072	2.937	6.033	-
RI (%)		23	0.9	80	-700	42	85

OK – ordinary kriging; RK – regression kriging; TASMMean: terrain attributes soil mapping using mean as a representative value without land use; TASMMeanLU: terrain attributes soil mapping using mean as a representative value with land use; TASMLandscape: terrain attributes soil mapping using landscape position as a representative value without land use; TASMLLU: terrain attributes soil mapping using landscape position as a representative value with land use MPE: mean prediction of error; RMSPE: root mean square of prediction error; RI: relative improvement

Among the best predictors, the OK showed the most inferior performance. This geostatistical method is known to be very sensitive to short-range variation (LASLETT; MCBRATNEY, 1990), and the large RMSPE can be ascribed to this. Nevertheless, the OK performed better than other methods for clay at LCW and total porosity at MCW. And also, when compared with TASM, the values of MPE are lower on general. OK is based on the assumption of randomly distributed spatial structure. This method might be more appropriate way when the complexity of pedogenesis is too large to be captured in a deterministic way (HERBST; DIEKKRÜ; VEREECKEN, 2006). Utset, Lópes and Díaz (2000) reported that soil properties were more precisely estimated for those whose CV was the lowest. In this work, MCW showed the lower values of CV and the OK performed better than LCW (higher values of RMSPE), when comparing the same physical properties.

RK takes into account the random component and the spatial structure of the target variables, derived from the spatial distribution of the auxiliary variable. So, the relationship between target soil property and auxiliary variables, represented by their coefficient of determination, is important in determining whether RK would outperform OK (KRAVCHENKO; ROBERTSON, 2007). In this study, low values of R^2 were found, generally, the R^2 for the prediction of soil properties is less than 0.5. Herbst, Diekkrü and Vereecken (2006) found R^2 from 0.20 to 0.55 in a correlation between soil hydraulic properties and terrain attributes, and RK outperformed OK on the topsoil. Zhu and Lin (2010) reported that RK outperform OK when R^2>0.2 and the spatial structure was well captured by the training data set (ratio of sample spacing over correlation range). López-Granados et al. (2005) and Sumfleth and Duttman (2008) pointed out that even the incorporation of a rather weakly correlated co-variable – but significant - into regression kriging tends to improve soil property prediction compared with OK. Zao and Shi (2010) reported that only 19.5% (R^2=0.195) of a total variation of organic carbon was explained by multiple linear regression between organic carbon and terrain attributes and NDVI attributes, and RK explained 65%. Besides the coefficient of determination, some studies also pointed out the importance of the strength of spatial variability (nugget/sill) in RK performance. Kravchenko and Robertson (2007) and Zhu and Lin (2010) reported that RK did not outperform OK for soil properties with nugget/sill <0.2 or $R^2<0.6$.

In this study, if the predictive variables can explain even a small part of the variation in the target variable (higher values of R^2), the RK outperforms OK because it exploits the extra information. And also, the summation of kriged errors due to regression, lead to smoothing of the predicted values, hence the reduction of RMSPE (ODEH; MCBRATNEY; CHITTLEBOROUGH, 1994). According to Bishop and McBratney (2001), even when only a poorly correlated secondary attributes are available, the hybrid methods may still perform better than OK. In this study, the RK outperformed OK when the strength of the relationship between soil properties and predictive variables is higher ($R^2>0.12$) and/or with stronger strength of spatial structure, which was found in LCW in organic matter, bulk density and total porosity prediction. Higher values of CV were found at LCW, where the higher number of samples should be necessary for accounting the spatial variability of physical properties. In this sense, kriging techniques, which are more data-driven, performed better than TASM. And also, at LCW, even if higher coefficient of determination for Ksat and drainable porosity, TASM performed better than others.

MCW showed weaker strength of spatial variability (N/S) and correlation between target and ancillary variables. With R^2 of 0.12, the RK did not outperform the OK in the total porosity prediction, but did for bulk density. The RK of clay, organic matter, drainable porosity and Ksat was not even performed, due the low coefficient of determination (R^2<0.06), because it result in pure kriging (no correlation) (HENGL; HEUVELINK; ROSSITER, 2007).

TASM performed better than OK and RK at MCW, and for drainable porosity and Ksat at LCW, which sources of variation of physical properties might be well accounted by TASM. Soil similarity vector of a local soil derived using fuzzy approach can be viewed as a non-linear transformation of environmental variables (ZHU et al., 2010). The hypothesis is the pedogenesis processes are creating a systematic order or pattern of soil properties distribution. This study considered soil properties varying in lateral directions, and such variation can follow systematic changes as a function of the landscape position, soil forming factors and/or soil management practices. The relationship between environmental and soil variables is not always linear and it is usually complex. Zhu et al. (2010) cited as an example of non-linearity and complexity the fact of a certain soil property might increase from a summit to backslope position and then decrease from backslope to footslope or depression positions. And also, soil properties tend to change gradually within well-defined landscape units but changes more quickly in transition zones between landscape positions. Considering the low or lack of significant linear relantionship between terrain and properties, due the reasons discussed, the TASM showed to be an adequate and sometimes more accurate than RK.

For those TASM methods that did not outperform OK and RK, it was found the highest values of MPE and RMPE. The choice of unrepresentatives values can increase the bias and lead to low accuracy of method. This fact points out the importance of the knowleadge of soil landscape relationships for TASM. The knowledge of a soil-landscape relationship in the field is essential to obtain a representative soil sample (SCHAETZL; ANDERSON, 2005). Comparing only TASM methods, those that incorporated land use in the model (TASMMeanLU and TASMlandscapeLU) at LCW performed better than those did not incorporate land use. This is demonstrated by the lower values of MPE and RMPE of the predictions. Even when the ANOVA test showed the land use has influenced significantly the physical properties, the use of land use map yields less accuracy of predictions at MCW. The only exception was organic matter.

In this study, considering only the way of choose typical values, the results show that TASMLandscape and TASMMean performed almost equally. The methods of accuracy assessment did not allow to detect any trend among methods. More studies should be considered in order to elucidate the best way of choose typical values in the regions studied. Zhu et al. (2010) applyed two different ways to choose typical soil properties values: representative values from existing soil survey of prescribed soil types, and properties values observed at a field location where the fuzzy membership of the local soil to the given soil type. Even in different landscapes, the use of values from soil survey showed to be a better representation of local soil property values.

Considering the improvement over the OK, which is a geostatistical technique that considers only the spatial autocorrelation of observed values in field samples, the values of RI (%) showed that the prediction accuracy can be improved by incorporating ancillary variables into prediction or using the knowledge based fuzzy membership approach.

3.5 Prediction maps

The DTMs and NDVI used for RK and TASM prediction, as well as land use classified map and hardened map (defuzzified) are presented in the Figures 5 and 6 for LCW and MCW respectively.

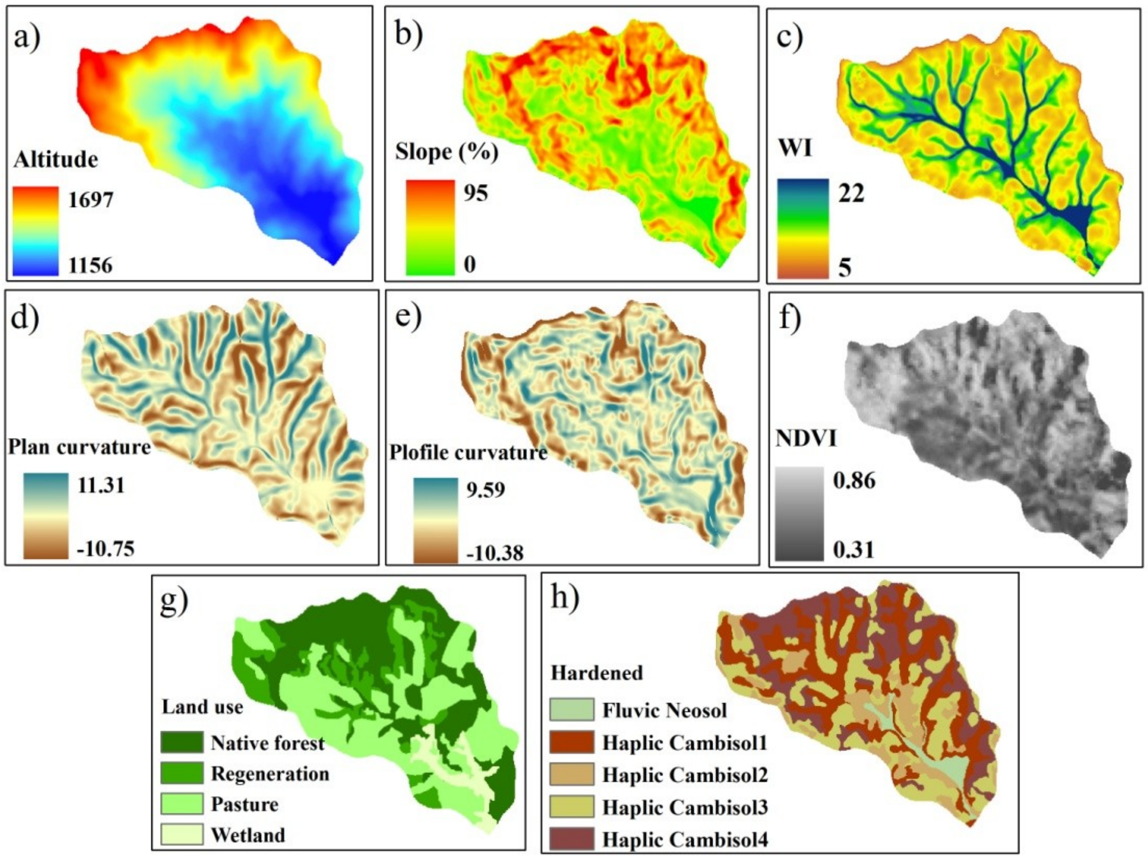

Figure 5 DTMs (a, b, c, d, e), NDVI (f), land use classified (g) and hardened map (h) at LCW

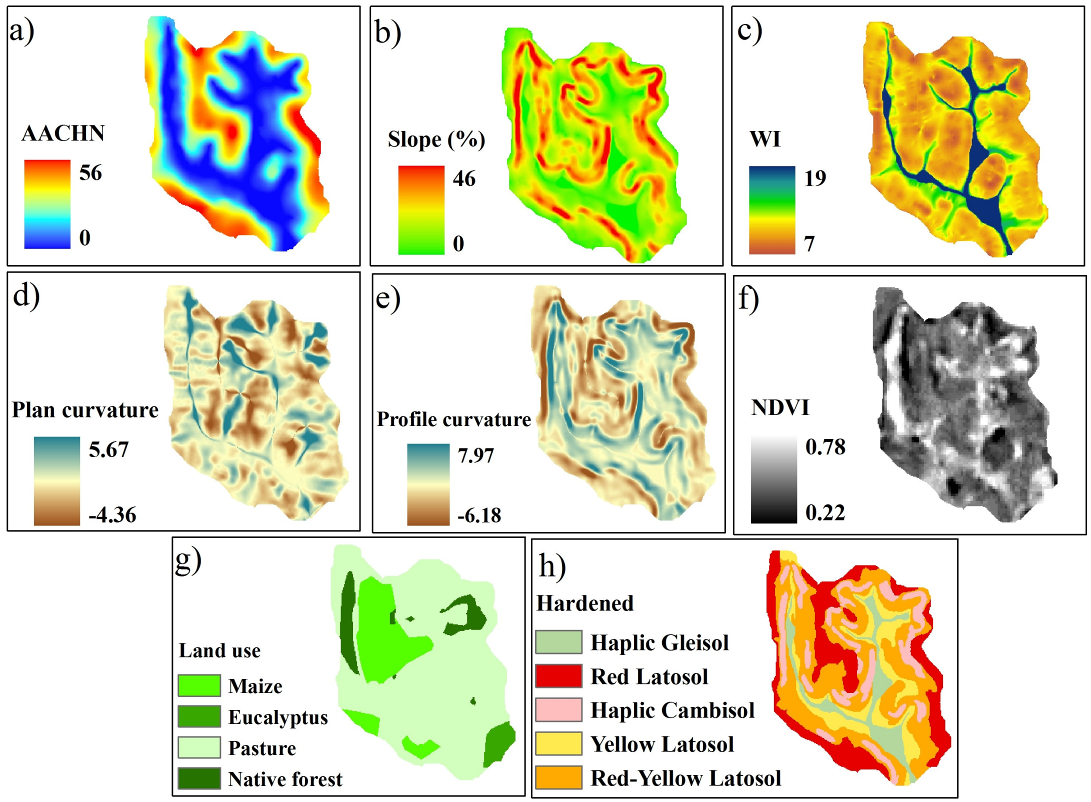

Figure 6 DTMs (a, b, c, d, e), NDVI (f), land use classified (g) and hardened map (h) at LCW

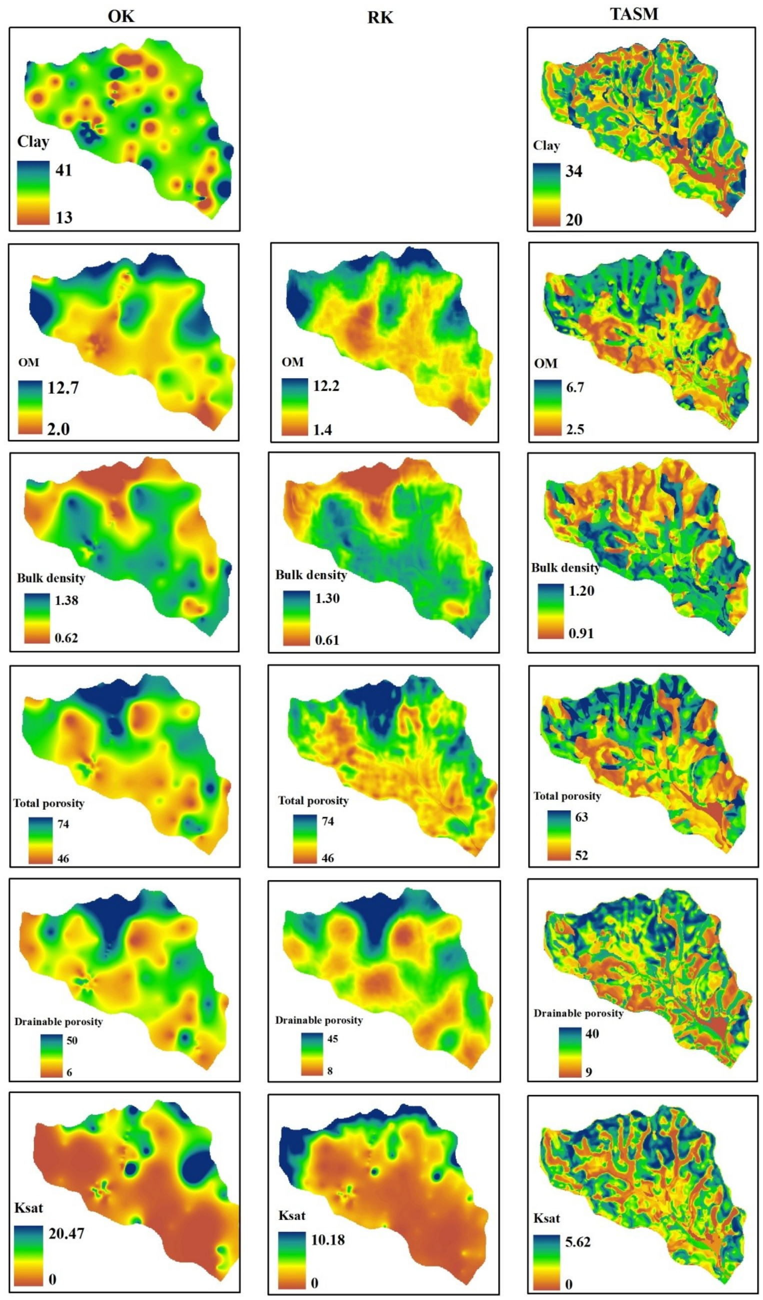

Figure 7 OK, RK and the best TASM prediction maps of soil physical properties at LCW

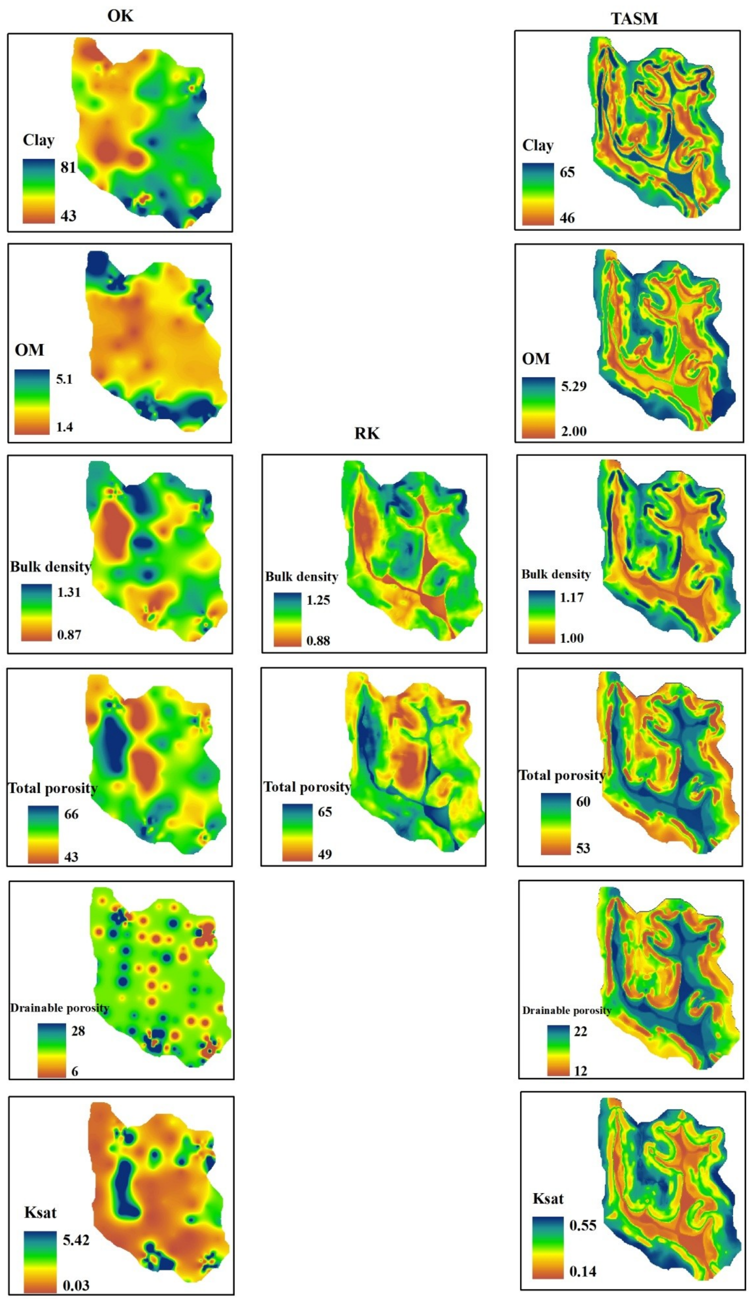

Figure 8 OK, RK and the best TASM prediction maps of soil physical properties at MCW

Figures 7 and 8 present the OK, RK and the best TASM prediction maps. The OK prediction maps show gradual transitions with fairly low level of detail. One limitation of this method, which the prediction have been based on an empirical model of soil variation, expressed in spatial terms, is the exclusion of information on soil-landscape relationships (MCKENZIE; AUSTIN, 1993). Another issue was the bulls-eye predictions in the maps of clay (MCW) and drainable porosity (LCW), probably due the short range of semivariogram and high nugget effect. Even if an unrealistic map, the values of MPE and RMPE pointed out OK as a clay best predictor. The RK maps reflects changes of the DTMs and NDVI were kept on multiple regression by the AIC criterion. And also, the RK, which uses auxiliary variables, has a more smoothing effect on minimising the influence of outliers on prediction performance (ODEH; MCBRATNEY; CHITTLEBOROUGH, 1994). The TASM has the advantage of incorporating the qualitative knowledge of the pedologist into spatial prediction as well as providing a more realistic portrayal of soil property variation. Because all the interpolation points were used to predict properties in OK and RK, the range of values predicted were quite similar to the original data set. However, because TASM predict properties using only one typical value per soil type, the range of predicted properties are somewhat different from the interpolation data set range. Therefore, if the data has a higher spatial variability, the TASM might not capture this variability in the prediction. On the other hand, in this study, some extreme values might be considered outliers (JUNQUEIRA JÚNIOR et al., 2008), especially at LCW where the CV is higher.

3.5.1 LCW

Except for clay content, the spatial variability of physical properties are clearly influenced by land use in this watershed. The pattern of physical properties is quite similar to land use. The relief seems to influence the forest cover indirectly, since pasture is preferably implanted in flatter and lower areas. And also, the higher organic matter content detected at higher altitudes was probably due to lower temperatures (RESENDE; LANI; REZENDE, 2007).

Organic matter has been identified as a major controlling factor in aggregate soils stability (ANGERS et al., 1997). Vegetation distribution controls organic matter (GESSLER et al., 2000), which in turn might explains the lower bulk density, higher total porosity, higher drainable porosity and Ksat in the same portions of the landscape, where the land use is forest natural regeneration (Figure 5G). The opposite situation happens in pasture areas. This spatial trend was accounted by the three prediction methods. Several studies have ilustrated the effects of converting forest into pasture upon soil properties, due to decrease of litter input, microorganism activity, bulk density and total porosity, and increasing compactation due the animal trampling, specially in topsoil (BERTOL et al., 2000; MENEZES et al., 2009).

3.5.2 MCW

When the RK was performed (bulk density and total porosity), the maps showed quite similar contours compared to TASM maps. It is possible to see the alluvium areas well captured by the saga WI (Figure 6c) and the profile curvature in the bulk density and total porosity prediction. The higher clay content in the *toeslope* of TASM maps suggests deposition and accumulation of the fine fraction eroded from upper slopes, caused by the erosion and runoff processes (SUMFLETH; DUTTMANN, 2008), and/or their deposition by creeks during flooding events. The organic matter prediction showed to be influenced by the land use, which higher values in native forest and eucalyptus areas on the east side of the watershed (Figure 6g). Lower values of organic matter were found under pasture areas, which is the predominant land use at this watershed. On the other hand, the accumulation of organic matter in the floodplains (low slopes and higher WI) was not accounted by OK. Water distribution in landscapes tightly controls soil C dynamics (GESSLER et al., 2000), and this trend is more clear in TASM maps, even though the floodplain did not show higher values of organic matter which may be due to the very high vertical and lateral spatial variability of characteristics, which is typical of these lowland environments (CURI; RESENDE; SANTANA, 1988). The prediction of organic matter by TASM also show higher values in the convex summit, in agreement to Rezende (1980). The author pointed out the combination of higher leaching, very low fertility, low temperatures in the past, and limited activity of microorganisms might contributed for the organic matter accumulation in this landscape position.

Differently from the other physical properties studied, the Ksat values represent the topsoil depth, but this property is also influenced by soil properties in deeper depths. Therefore, the spatial variability of this soil property might be related to properties better expressed in the B horizon of soils that were not accounted for in any of the models. Higher values of Ksat were found in Latosols (Figure 6h and 7), where the good physical properties are mainly influenced by aggregate stability, as already mentioned before. This trend was not followed by the total porosity and drainable porosity in the TASM maps. In the topsoil, even for Latosols, the frequent wetting and drying cycles could be responsible for the decrease in aggregate stability (CARON; KAY; STONE, 1992), where the granular structure behaves as a blocky structure (AJAYI et al., 2009). Lower values of bulk density and higher values of total porosity were found in areas with relatively higher values of organic matter in the TASM maps, as well as in the native forest area. Even though these attributes were not correlated with NDVI by the AIC criterion in the regression analysis, the land use, which in turn influenced organic matter, was able to explain the spatial variability of most of the physical attributes. This fact reflects the compaction by the cattle in pasture areas, whose pressure applied by the animal trampling increase bulk density and decrease total porosity and drainable porosity, mostly in the first centimeters of depth (BERTOL et al., 2000).

4 CONCLUSIONS

The same soil physical properties can be predicted in different ways, as long as different pedogenic factors and land uses control soil properties distribution in each watershed, and soil properties often display contrasting scales of variation. Ancillary variables and predictive methods can be useful in one site study, and inappropriate in another one.

The selection of interpolation methods can vary between regions with contrasting soil-landscape relationships. The knowledge and fuzzy logic used in TASM prediction provided a better estimate for the spatial variability of soil properties for the MCW, where the physical properties seem to follow a systematic patter of distribution, due to pedogenesis. Another reason is the prediction method can be considered as a non-linear transformation of the data. The TASM estimates of soil properties is an adequate accurate option considering: 1) the low correlation or no correlation between DTM and NDVI and physical properties; 2) the high cost of an intense sampling scheme; and 3) the scarce resources for that in Brazil.

The data-driven RK usually performed better at LCW. Comparing to MCW, higher coefficient of correlation suggests a stronger relationship between contemporary landforms and soil properties, coupled with the fact of more data would be necessary for accounting higher spatial variability at LCW (higher CV values of physical properties). Besides the relief and soil, the land use markedly explained the spatial variability of the physical-hydrological properties at both watersheds. It became clearer with prediction maps as well as ANOVA test.

The kriging methods can be considered data-driven, and TASM method is knowledge-driven. The combination of both methods should be considered to capitalize on the best attributes of both models.

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CHAPTER 4

Knowledge based inference maps for predicting the groundwater recharge potential in different sites of Alto Rio Grande region, state of Minas Gerais, Brasil

ABSTRACT

The downward flow of water towards to the water table, adding to the groundwater reservoir is defined as direct recharge. The quantification of the groundwater recharge rate is important for an efficient and sustainable groundwater use and consequently water resource management. Thus, this work aimed at the spatial prediction of the groundwater recharge using fuzzy logic as well as provided background information on the potential controls on groundwater recharge, at two watersheds at different physiographical regions, in Alto Rio Grande Region, State of Minas Gerais, Brazil. Lavrinha Creek Watershed (LCW) is a headwater watershed located in Mantiqueira Range physiographical region. The main soil class is Cambisol and the predominant vegetation is Atlantic Forest and grassland. Marcela Creek Watershed (MCW) is representative of Latosols and is located in Campo das Vertentes physiographical region and the predominant soil use is grassland. In both sites part of the native forest has been converted into pasture. The proposed indexes or typical values for the recharge prediction are based on the soil classes, soil properties, surface topography and land use. Fuzzy logic was applied in integrating the data to accommodate the spatially continuous nature of groundwater recharge. Some hydrologic indicators were analyzed in both sites in order to validate the methodology proposed. We have found important relationships between the recharge potential predicted based on the indexes and the hydrological responses of watersheds. The index of potentiality of aquifer recharge based on the fuzzy membership values and the vector of similarity showed to be proper for mapping the potential of recharge in a continuous way, accounting for complex interactions among soils, landscape and land use features. The prediction maps as well as hydrological indicators pointed out that LCW has higher potentiality of groundwater recharge, due to the role of Atlantic Forest and the precipitation regime. Even though the geomorphic characteristics at MCW are more favorable for groundwater recharge, the predominance of pasture along with the precipitation regime, were responsible for the lower potentiality of groundwater recharge. Since the base flow can be considered as the outflow of the groundwater reservoir feeding the rivers during rainless period, making them more perennial, in order to increase the water yield for public use, the maintenance of Atlantic Forest at LCW, or the use of conservationist practices at MCW are both recommended.

Keywords: Water infiltration. Base flow. Surface runoff. Soil classes. Fuzzy logic.

1 INTRODUCTION

Direct recharge is defined as the downward flow of water that reaches the water table, forming an addition to the groundwater reservoir (VRIES; SIMMERS, 2002). The quantification of groundwater recharge rate is important for efficient and sustainable groundwater uses and for an water resource management. Despite a long history of investigation, the complex interaction of the factors that influence the rates and locations of recharge and discharge areas remains unclear (SCANLON; HEARLY; COOK, 2002). As widely appreciated among hydrogeologists, groundwater recharge is also one of the most difficult parameters to quantify (STONE; MOOMAW; DAVIS, 2001). Understanding and quantifying groundwater recharge and the attributes that govern it is crucial for developing effective management for water supply.

In this sense, two watersheds were chosen for this study, according to their representativeness in two different physiographical regions of Southern Minas Gerais, Southeast Brazil: Mantiqueira Range and Campo das Vertentes physiographical regions. Minas Gerais is the second state in terms of population in Brazil (more than 18,000,000) and the second largest economy (Gross Domestic Product of US$ 43.2 billion). Both study sites are located in Grande River Basin, which is an important producer of hydroelectric energy. Nowadays, three hydroelectric reservoirs have flown directly from the Grande River drainage basin. The potential electric energy of these facilities is greater than 200 MW, which is essential to the development of Minas Gerais (FUNDAÇÃO JOÃO PINHEIRO, 2004). The maintenance of hydrological characteristics of the Grande River Basin is monitored by the governmental agency associated with energy planning for State of Minas Gerais in the next decade. It is also, important to highlight the Mantiqueira Range role on water production, whose region is the most important headwater region in southeast Brazil (MELLO et al., 2008).

Besides the economical and social problem, an important environmental issue in both regions is associated to the native forest that has been replaced by extensive pasture or by crops with degraded lands. Several consequences have been reported: decreasing of soil quality expressed in terms of physical properties and water infiltration (ALVARENGA, 2010; MENEZES et al., 2009); increasing in soil losses and water erosion (GIAROLA, 1994; SILVA et al., 2008); higher fluctuation of soil moisture due the low vegetation cover which increase the surface runoff (MELLO et al., 2011); and decreasing of the spring's flow that influences the temporal dynamic of specific water yield (JUNQUEIRA JÚNIOR, 2006; MENEZES et al., 2009).

Hydrologic monitoring as well as soil survey in semi-detailed scale in Alto Rio Grande Region have been carried out (MENEZES et al., 2009; MOTTA et al., 2001). These databases and interpretations, combined with land use raster maps, can be the source of a fast initial estimation of groundwater recharge potential. For that, according to Alvarenga (2010), the development of indexes can help the identification of areas with more capability to promote the soil water infiltration and consequently, direct recharge. The spatial variability of these indexes can help scientists and engineers to design more accurate and cost-effective research plans and management strategies (LIN; WANG; VALOCCHI, 2008). Considering that groundwater interacts with the watercourse, this type of study is relevant since important rivers and hydropower plants reservoirs are fed by aquifers draining from these regions. The interpretation of soil and land use for potentiality of aquifer recharge using crisp boundaries has been developed (ARAÚJO, 2006; MENEZES et al., 2009). Thus, the use of fuzzy membership values should be more realistic in representing this spatial phenomenon as a continuum. This type of approach also allows the interaction between Pedology and Hydrology, which is desirable due to the wealth of pedological information.

This type of study can promote an important advance on the understanding and predicting water distribution in soils and landscapes, whereas advances of hydrology can enrich interpretation of soil properties (PACHEPSKY; RAWLS; LIN, 2006). Deep percolation in humid areas is mainly controlled by atmospheric water balance (rainfall minus potential evapotranspiration). Soil water infiltration, storage and transport capacity of the sub-surface (VRIES; SIMMERS, 2008) occur as the consequence of this water balance. However, variations in attributes such as soil classes, surface topography, soil depth, physical-hydrical properties and land use exert influence on the water movement in different ways (SCHAETZL; ANDERSON, 2005). As long as these attributes are spatialy distributed, the geographical information system (GIS) and fuzzy logics have a potential for processing, aggregating and creating terrain attribute derived from soil maps. A knowledge-based digital soil mapping along with fuzzy membership values have been used extensively to predict soil classes and soil physical-chemical properties (MCKAY et al., 2010; ZHU; BAND, 1994; ZHU et al., 1997, 2001, 2010), since these properties are inherent to soils and landscape.

In the context described above, this work proposes the development of indices for predicting the potential of aquifer's recharge based on soil classes, soil hydrology properties, landscape and land use, using a fuzzy logic approach. It employs an expert system methodology for integrating empirical knowledge, with environmental data (e.g. digital terrain model and land raster maps) for the derivation of information about groundwater recharge. The approach also incorporates fuzzy logic into the data integration process to accommodate the spatially continuous nature of groundwater recharge (ZHU; BAND, 1994). Some hydrologic indicators were also analyzed with the purpose to promote the validation of the indexes. It also provides background information about the potential controls on groundwater recharge.

2 MATERIAL AND METHODS

2.1 General characteristics of study sites

This study was conducted in two watersheds located in Southern Minas Gerais state, southeast of Brazil (Figure 1). Both watersheds are representative of the Alto Rio Grande basin and are located in different physiographical regions. LCW is a typical headwater watershed located in Mantiqueira Range region. Inside this watershed, a micro-catchment (16 ha) occupied entirely by Atlantic Forest has been monitored since 2009 (MC-LCW). MCW is representative of Latosols and is located in Campo das Vertentes region. The planning units have been extremely important in establishing strategies for development according to the characteristics of the respective watershed (BESKOW et al., 2009). More characteristics of study sites are presented in the Table 1.

Alto Rio Grande region is an important hydrological region due to its energy electric potential on the basis of hydraulic energy. Nowadays, there are three important hydropower plants in full production, whose total capacity installed is around 200 MW. Moreover, the rivers that flow from the region feed one of the most important hydropower plant of Brazil, named Furnas, which in turn supplies great part of Southeast Brazil.

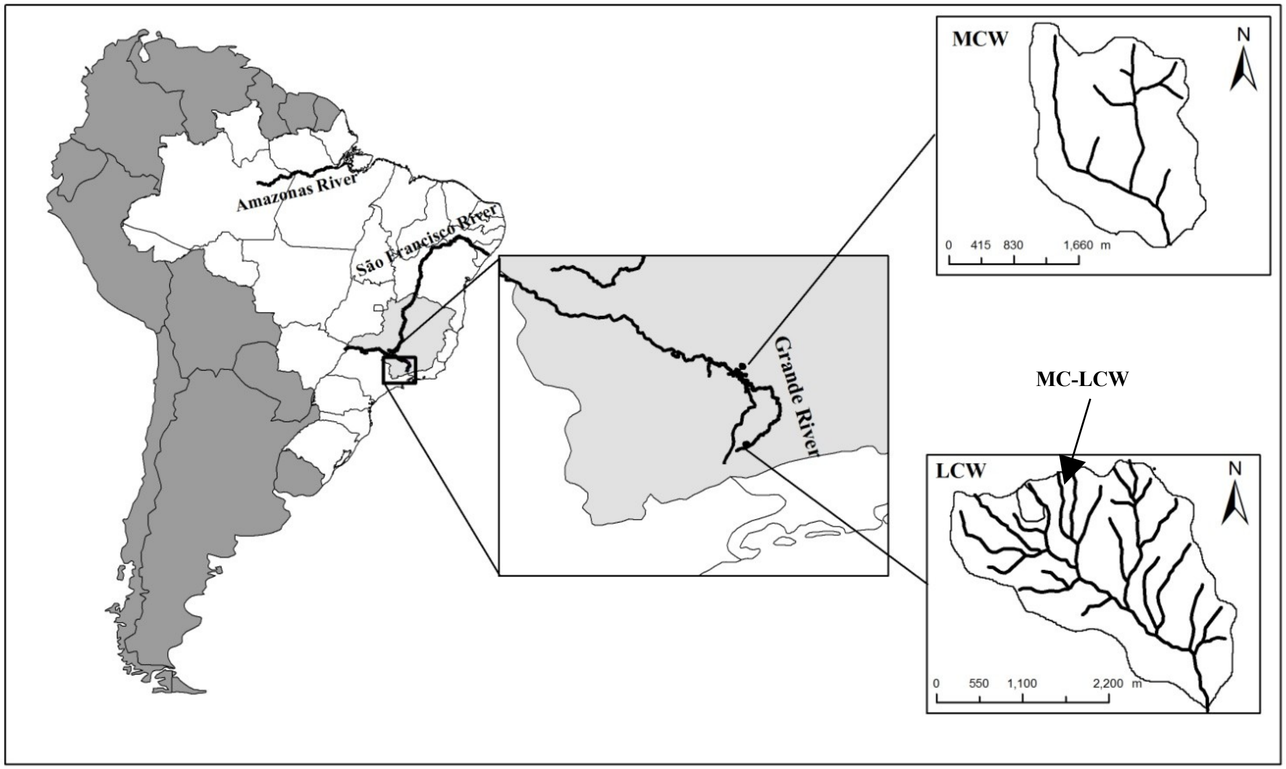

Figure 1 Geographical location of the LCW, MC-LCW and MCW

Table 1 Basic characteristics of the study sites

	LCW	MCW
Location	Between latitudes S 22º6'53.7" and 22º8'28.1" and longitudes 44º26'21.1" and 44º28'39.2"	Between latitudes S 21º14'27.8" and 21º15'51.9" and longitudes 44º30'58.0" and 44º29'29.2"
Area	676 ha	470 ha
Elevation	From 1151 to 1687 m	From 957 to 1057 m
Mean annual temperature[1]	15°C	19.7°C
Annual Precipitation[2]	2000 mm	1300 mm
Land agricultural suitability	Fauna and flora reserve	Crop

1Souce: Antunes (1986); [2]Souce: Geominas (2011)

2.1.1 Land use

LCW is composed of 41.5% of native forest, 13.2% of natural regeneration, 40.4% of pasture, and 4.9% of wetlands (Figure 2). The native forest is a typical Atlantic Forest with the canopy's height varying from 4 (shallower soils) to 25 m (thicker soils), with emergent trees reaching up to 40 m in dense wooded areas. The deciduousness has low expression during the dry or cold season (less than 20%). In Minas Gerais, this type of vegetation is strictly located in mountainous regions, in elevations above 900 m, mainly in moist slopes at Mantiqueira Range region (OLIVEIRA FILHO et al., 2006). The relief seems to influence the forest cover indirectly, since the pasture is preferably implanted in flatter and lower areas. The higher organic matter content detected in higher altitudes is probably due to the erosion coming from the coast to hinterland, protecting these areas from renewal process (geological erosion), where is possible to find evidences of paleoenvironments from Pleistocene (BIGARELLA; ANDRADE-LIMA; RIEHS, 1975; RESENDE; LANI; REZENDE, 2002).

The land use at MCW consists of 72.7% pasture, 17.4% maize, 6.9% native forest and 3% eucalyptus (Figure 2). The native forest is Cerrado, a woody savanna, whose variety spreads from dense woodlands with a tree height of up to 15 m to nearly treeless grassland areas with only few or no shrubs (OLIVEIRA FILHO et al., 2006), and more or less recognizable stages of this continuum are given vernacular names (OLIVEIRA FILHO; RATTER, 2002). Considering the environment and geographical distribution, the Cerrado is found in well drained and acid soils, mainly Latosols or Inceptisols. The climate is seasonal (dry and rainy seasons are well defined) with high risk of fire during the dry season (OLIVEIRA FILHO et al., 2006) and presents typical monson characteristics. Atlantic Forest and Cerrados are threatened by the anthropogenic activity in Brazil. As a result, the native forest in the study regions has been replaced by pasture or crops without conservationist practices.

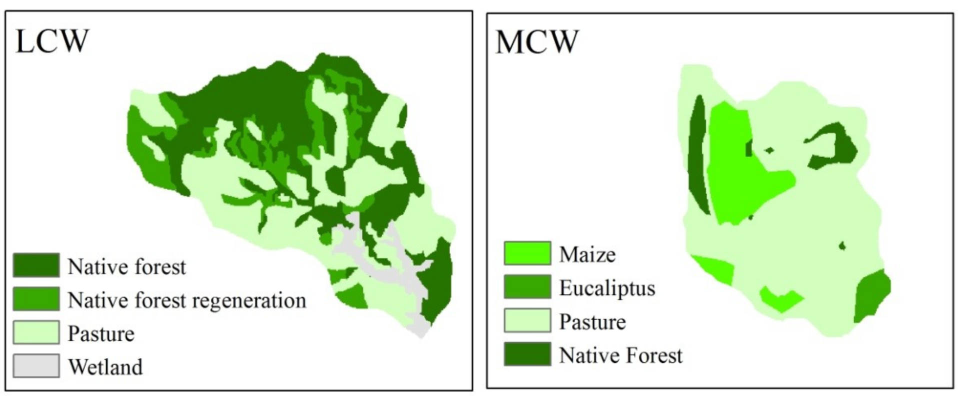

Figure 2 Land uses at MCW and LCW

The conversion of natural ecosystem can influence soil properties, which in turn can influence water infiltration and groundwater recharge. The different types of land use can enhance the water infiltration not only by the effect of canopy interception, but also by improving physical-hydrolgic soil properties, through the effect of organic matter, litter, rhizosphere, microorganisms, and others. In this study, soil classes and land uses were combined to create soil types. In order to assess if the physical property is significantly influenced by different types of land uses, analysis of variance (ANOVA) were made by F test ($p<0.01$ or $p<0.05$) (Table 2 and 3). The box-cox procedure (BOX; HUNTER; HUNTER, 1978) was carried out to determine the suitable type of transformation for ANOVA. Drainable porosity, total porosity (at LCW) and Ksat (at MCW) were log transformed. The statistical analyses were performed in SAS software version 9.2 (STATISTICAL ANALYSIS SYSTEM INSTITUTE - SAS INSTITUTE, 2008).

2.1.2 Parent material

The term parent material encompasses the general physical, chemical, and mineralogical composition of the unconsolidated material, mineral or organic, in which soil are formed. Mode of deposition and/or weathering may be implied by the name. LCW has the alluvial material transported by water and the massive rock gneiss as a parent material. The lithological unit is fractured (CENTRO TECNOLÓGICO DE MINAS GERAIS - CETEC, 1983) thus contributing to the storage and transmittence of water that could be limited if the permeability and flow are moderated or low in within the fractured rocks. Besides the alluvial, MCW has a predominance of metapellitic rocks with phyllite and schist texture. They are fine grained and have a highly metamorphosed nature that results in low matrix porosity (ABBOTT; BIERMAN, 2000). These rocks have lower potential of aquifer recharge when compared to gneiss (ARAÚJO, 2006).

2.2 Fuzzy logic and the choice of typical values

In order to predict the potentiality of aquifer recharge, the following steps were carried out, adapted from Libohova (2010):

a) establishing soil-landscape relationships;
b) quantifying relationships between soils and terrain attributes and formalizing these relationships in a set of rules that relates to raster maps;
c) creating soil property maps;
d) choose the typical values of a recharge potential.

a) Establishing soil-landscape relationships.

Considering the soil-landscape relationships at LCW, the alteration of gneiss resulted in predominance of Cambisols (moderately developed and well drained soil classes). The relief is steep with concave-convex hillside, predominance of linear pedoforms and narrow floodplain (CETEC, 1983; RADAMBRASIL, 1983). Hydromorphic soils occupy the toeslope position, where the water table is near to the surface in most part of the year.

MCW is located in Campos das Vertentes Plateau geomorphological unit where the dissection pattern is homogenous (CETEC, 1983; RADAMBRASIL, 1983). The relief is gentle with intense soil development. Latosols are the most expressive soil class. Considering that the relationship of soils and their environments (JENNY, 1941), the Latosols were formed on stable and very old surfaces conductive to intense weathering-leaching under warm and moist climate, where the organisms are very active. Together, the individual factors contribute to the formation of highly weathered tropical soils (MOTTA; CURI; FRANZMEIER, 2002). Latosols are associated with Cambisols (GIAROLA et al., 1997) that occupy the more dissected positions (MOTTA et al., 2001), and more linear portions inside a convex macropedoform in the landscape. Hydromorphic soils occupy the youngest surface on the toeslope positions.

Red Latosols (2.5YR or redder) generally occupy flatter and convex summit positions. The Yellow (7.5YR or yellower) and Red-Yellow (less redder than 2.5YR and redder than 7.5YR) Latosols occupy landscape positions from the summit to footslope positions. These colors show a preterit hydrological influence, where the type of orientation of parent material layers, by conditioning a different moisture regime in two systems, exerted influence on the pedogenesis of the Red, Yellow and Red-Yellow Latosols. The horizontal orientation of the layers conditioned the genesis of the Yellow and Red Yellow Latosols, having higher goethite/hematite proportion and consequently, yellowish colors, as the result of former moisture soil conditions that were different than in redder soils (CHAGAS et al., 1997). The inclined orientation of the layers conditioned, under similar conditions, the formation of Red Latosols having better drainage and higher weathering-leaching, higher hematite/goethite proportion and, consequently, reddish colors. Nowadays, due to the current climate conditions, the soils are well drained. The present pedogenetic environment is favoring kaolinite stabilization and goethite formation, removing hematite and being probably responsible for the yellowing (xanthization) of superficial horizons (DUARTE et al., 2000; MOTTA; CURI; FRANZMEIER, 2002).

b) Quantifying relationships between soils and terrain attributes and formalizing these relationships in a set of rules that relates to raster maps.

Threshold values were identified and assigned to each soil map unit, according to soil scientists' knowledge, and to a soil map from previous soil survey and profile description (CHAGAS et al., 1997; MENEZES et al., 2009;

MOTTA et al., 2001). Soils were classified according to Brazilian Soil Classification System (EMPRESA BRASILEIRA DE PESQUISA AGROPECUÁRIA - EMBRAPA, 2006). The relationship between soil and landscape established in the step 1 were quantified using digital terrain models (DTMs).

Analogous to a digital elevation model (DEM), a DTM is an ordered array of numbers that represent the spatial distribution of terrain attributes across a landscape in a raster-based format (BISHOP; MINASNY, 2005). Terrain models were based on a 30 m resolution DEM, generated from counter lines with 1:50.000 scale (INSTITUTO BRASILEIRO DE GEOGRAFIA E ESTATÍSTICA - IBGE, 1973). The sinks were filled and hydrologic DEM was created. In order to calculate the terrain attributes from DEM, the SAGA GIS 2.0.6 (BÖHNER et al., 2010), ArcGIS spatial analyst (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE - ESRI, 2010) and an extension ArcGIS extension Soil Inference Engine (ArcSIE), version 9.2.402 (SHI, 2011) were used. The following primary (calculated directly from DEM) and secondary (calculated from the combination of two or more primary terrain attributes) terrain attributes were extracted from DEM:

a) primary: slope is the gradient of elevation. Profile curvature is the direction of the maximum slope and is, therefore, important for water flow. Plan curvature is transverse to the slope, which measures the convergence or divergence and hence the concentration of water in a landscape (MOORE et al., 2003);
b) secondary: altitude above the channel network (AACHN) describes the vertical distance between each cell of a grid and the elevation of the nearest drainage channel cell connected with the respective grid cell of a DEM. SAGA wetness index (WI) was used instead of well known topographic wetness index ($ln(a/tan\beta)$), where a - ratio of

upslope contributing area per unit contour length and β - the tangent of the local slope). Both wetness indexes are similar, however, in SAGA is possible to adjustment the width and convergence of the WI multidirectional flow to single directional flow. Large WI values indicate an increase likelihood of saturated conditions and are usually found in lower parts and convergent hollow areas and soils with small hydraulic conductivity or areas of small slope (BEVEN; WOOD, 1983). These indices have been used to identify water flow characteristics in landscape (SUMFLETH; DUTTMANN, 2008).

The knowledge about the soil-landscape relationships can be qualitatively modeled using DTM, since the terrain attributes represent soil and hydrologic processes. Thus, a qualitative soil landscape model cited in the first step was used to quantify soil-landscape relationships on a continuous basis, based on different terrain attributes and their ranges. For the model development, a set of rules for the entire watersheds were created using the ArcSIE.

At LCW, higher values of WI and low slopes were used for mapping hydromorphic soils in flatter alluvial areas (footslope). The Inceptisol occupies the well drained portions of landscape with lower values of WI (summit, shoulder and backslope) formed by different combinations and ranges of slope, plan and profile curvature. The environmental control variables and their ranges are presented in the Table 2.

At MCW, the Red Latosols usually occupy flatter summit positions in a more convex pedoform, expressed by higher values of AACHN, lower values of slope and negative values of plan curvature. The Yellow and Red-Yellow Latosols are present on the shoulder, backslope and footslope positions (intermediate values of AACHN and gentle slopes). Two instances were applied for Inceptisol: one considering steeper slopes, and another for plan and profile curvatures. These instances were integrated using multiplication of functions. Hydromorphic soils (Haplic Gleisols) are located in lower AACHN and higher values of WI. The ranges of environmental variables are presented in Table 3. The ArcSIE interface, as well as the shape of curves, can be seen in McKay et al. (2010).

Table 2 Environmental control variables of soil classes at LCW

Soil type[1]	Full membership				
	Altitude	Slope	WI	Plan curvature	Profile curvature
FN	1156	1	15-21	-	-
HC1	-	32.5	7	1	2.3
HC2	-	15	7	-1	0
HC3	-	32.5	7	-1	0
HC4	-	51	7	-1	0
	50% membership				
FN	1200	10	14,22	-	-
HC1	-	19.5,45.5	0,14	0.11.3	1.56,9.5
HC2	-	10,20	0,14	-11,0	-1.5,1.5
HC3	-	19.5,45.5	0,14	-11,0	-1.5,1.5
HC4	-	45-95	0,14	-11,0	-1.5,1.5
	Curve shape				
FN	Z	Z	Bell	-	-
HC1	-	Bell	Bell	Bell	Bell
HC2	-	Bell	Bell	Bell	Bell
HC3	-	Bell	Bell	Bell	Bell
HC4	-	Bell	Bell	Bell	Bell

[1]FN – Fluvic Neosol; HC – Haplic Cambisol

Table 3 Environmental control variables of soil classes at MCW

Soil type[1]	Full membership				
	AACHN	Slope	WI	Plan curvature	Profile curvature
GX	0.1	-	15.5	-	-
RL	23.53	2.7	-	-0.9	-
HC	4	30	-	-1	-1.75
YL	5	5.5	-	-	-
RYL	5	14	-	-	-
	50% membership				
GX	1.5	-	14.5,19	-	-
RL	20,56	0,10	-	-4.3,0	-
HC	2,23	20	-	-2.3,-1.1	-4.35,-0.75
YL	2,15	3,8	-	-	-
RYL	2,23	8,20	-	-	-
	Curve shape				
GX	Z	-	Bell	Bell	-
RL	Bell	Bell	-	-	-
HC	Bell	S	-	-	Bell
YL	Bell	Bell	-	-	-
RYL	Bell	Bell	-	-	-

[1]HG – Haplic Gleisol; RL – Red Latosol; HC – Haplic Cambisol; YL – Yellow Latosol; RYL – Red-Yellow Latosol

The terrain attribute values and ranges associated with each soil map class were used to define membership functions. ArcSIE, designed for creating soil maps under fuzzy logics, supports a knowledge based approach to establishing the relationships between soil and its environment, providing tools for soil scientists to formalize the relationship based on pedological knowledge of the local soils. The membership functions referred to as optimality functions as they define the relationship between the values of an environmental feature and soil type. The Rule-Based Reasoning (RBR) inference was used to define the relationship between values of an environmental variable and a given soil class (SHI, 2011).

c) Creating soil property map (groundwater recharge potential)

The soil-landscape relationships were extracted and the characterized environmental conditions were linked through a set of inference techniques to populate the similarity model for a given area (ZHU; MACKAY, 2001). Thus, based on fuzzy membership values, the continuous variation of soils can be represented by continuous potential of recharge maps derived from the similarity vectors, using the following formula (Zhu et al., 1997):

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

where V_{ij} is the estimated potential of recharge value at location *(i,j)*, V^{k} is a typical value of soil type *k* (e.g. Haplic Cambisol under native forest), and *n* is the total number of prescribed soil classes for the area. If the local soil formative environment characterized by a GIS resembles the environment of a given soil category, then property values of the local soil should resemble the property values of the candidate soil type. The resemblance between the environment for soil at (*i,j*) and the environment for soil type *k* is expressed by , which is used as an index to measure the level of resemblance between the soil property values of the local soil and those of soil category (ZHU et al., 2001). The property value can be any property that shows a recognizable pattern or relationship with the terrain attribute or landscape position (LIBOHOVA, 2010). The higher the membership of a local soil in a given soil type the closer the property values (potential of recharge) at that location will be to the typical property values (ZHU et al., 2010).

Different land uses were also considered in the prediction because they affect physical properties, as showed by ANOVA test, and groundwater recharge. Landsat images were classified with support of field observations, and polygons with same land use were created. In ArcSIE, land use raster maps were used as categorical data (data do not have quantitative meaning, values are only for labeling or categorizing different land uses), and were overlaid with all soil classes, using the function type Nominal (SHI, 2011). The way of chosen typical values (V^k) for the soil types *k* (soil overlaid with land use) is detailed in the next step.

d) Choosing typical values of a direct groundwater recharge

Considering that each soil type brings information about the parent material, surface topography, solum depth, morphology (texture and structure) and the respective land use, empirical scores related to the potentiality of groundwater recharge were created for each of those features. The sum of scores consists of the typical values (V^k). The greater the potential of groundwater recharge, the greater the typical value of the soil type. Considering the extreme situations, if one ideal soil type has the best conditions to groundwater recharge, it should score the maximum values and consequently will get the highest typical value (100). The opposite situation happens if the soil is located in discharge areas in the landscape, or low potential of recharge. The sum of scores is 0, as well as the typical value. 50% of the scores are related to soil and landscape features, and 50% related to land use. The scores were set up considering the situations within the two study sites. The scores into soil and landscape features were divided. The maximum score for the parent material (geology) is 10, soil-landscape is 15, solum depth is 15, and morphology (texture and structure) is 10, and are discussed individually below.

The geology represents the groundwater storage volumes itself. If the bedrock is massive, without fractures, may not store significant quantities of water. In many areas, the crystalline bedrock is associated with very low porosity and storage, but lends itself to the development of thick saprolite overburden that may store and transmit substantial quantities of water (MWAKALILA; FEYEN; YESURE, 2002). In this study, the main contrast will be between a massive fractured bedrock (LCW) and metapellitic rocks (MCW).

A combination of different digital terrain models were firstly used to map soils, as presented earlier in the environmental control variables (Table 2 and 3). Since they are good predictors of soil patterns and show the changes of surface and soils along the landscape, they can be related to the rate of water flow. Scores of soil surface were set up according to these features for each soil class. Higher scores were given for soils on the surfaces with higher potential of water infiltration. In addition to its influence on subsurface flowpath distribution and transit times, surface topography also relates to the distribution of shallow storage (PRICE, 2011). Soils and surface are closely related. Soils vary along catenas for two main reasons: the slope affects fluxes of water and matter (generally in the downslope direction) and consequently the water table fluctuation (SCHAETZL; ANDERSON, 2005) is also affected. The effect of orientation of parent material layers is also a controlling factor on soil-landscape distribution.

Along with surface relief, the subsurface topography and solum depth exerts strong influence on water storage and through flow pathways. It determines the water storage capacity in terms of volume. The thicker the soil, the greater the storage potential which relates to higher capacity of water storage and vertical infiltration. Also, if water finds any impediment layer, the lateral flux dominates (HUTCHINSON; MOORE, 2000). Thus aquifer recharge decreases. Comparing the watersheds, the main contrast is between the very deep Latosols (higher scores) and the shallow or deep Cambisols (lower scores).

The morphology (texture and structure) of soils were also considered in the potential of groundwater recharge scores. In Brazil, the description of soil profiles usually does not bring physical-hydroligic measures, e.g. saturated hydraulic conductivity (Ksat), bulk density, or drainable porosity. However, texture and sulfuric attack are commonly measured and structure is always described. It is well known that texture and structure properties are closely related to water movement (DOOD; LAUENROTH, 1997; YAKLEY et al., 1998). Thus, they can be used to draw inferences about water infiltration.

The topsoil (0-15 cm) was sampled and physical properties were measured in both watersheds. A total of 198 points were sampled at LCW, following the regular grids 300 x 300 m and refined scale 60 x 60 m and 20 x 20 m, and two transects with the distance of 20 m between points. A total of 165 points were sampled at MCW, following the regular grids 240 x 240 m and refined scale 60 x 60 m. The soil properties determined were bulk density by the volumetric ring method (EMBRAPA, 1997); organic matter according to Walckley and Black (1934); drainable porosity was calculated by the difference between saturation moisture and soil moisture at field capacity (MELLO et al., 2002); and saturated hydraulic conductivity (Ksat) were determined *in situ* by constant flow permeameter (Ghelph permeameter - model 2800KI). The average values of soil properties were calculated within soil type. Also, one profile description was conducted for each soil class, whose texture, structure and sulfur attack results were analyzed for each soil layer.

2.3 Hydrologic indicators from watersheds

In order to validate the indexes created for the groundwater recharge potential, some hydrological indicators were analyzed in both sites. Precipitation data were logged at 15-minutes intervals as well as the total flow every 30 minutes since 2006 respectively by a meteorological and fluviometric stations. After the hydrograph structure, base flow was separated from total flow, considering exponential depletion of hydrograph recession (base flow), and then, it was related to the total flow, precipitation and evapotranspiration regime, in a monthly interval. This interval is typical for evaluating the behavior of the base flow process due to its slow depletion, with few changes in discharges throughout the time (TUCCI, 2001).

A micro-catchment (MC-LCW) has been monitored since 2009, which is entirely occupied by Atlantic Forest inserted in LCW (Figure 2). This micro-catchment has drainage area about 16 ha and the monitoring consists in a complete observation of hydrological cycle elements outside and inside of the forest. The results were also presented on the basis of hydrograph associated to the hydrological year on the region (Set/09-Aug/10).

Base flow depends on the water stored in the aquifers and their properties of water transmission (PRICE, 2011), decreasing exponentially through time. It can be represented by the Maillet equation:

$$Q_t = Q_{t0} * e^{-\propto(\Delta t)}$$

where Qt is the discharge ($m^3\ s^{-1}$) at time t, Q_{t0} is the initial discharge at time zero, Δt is the time elapsed (days) between Qt and Q_{t0}, and α is the recession coefficient.

The groundwater recharge indexes should be in agreement with the hydrological indicators, which in turn promote a better understanding the factors that control recharge. Factors that promote infiltration and recharge of subsurface storage will increase base flows (PRICE, 2011). Thus, the watershed classified with higher values of potential of groundwater recharge should have higher values of the base flow, in relation to the precipitation in the period. This work focused on water movement towards the aquifer and raised some factors that can hamper it. However, recharge can be broadly defined as water that reaches an aquifer from any direction (down, up, or laterally) (LERNER, 2007).

3 RESULTS AND DISCUSSION

3.1 Scores and the typical values of potentiality of groundwater recharge

The scores created in order to make the typical values of groundwater recharge related with soil features and land use, as well as the sum of these values (typical values), are showed in Table 4 and 5. Gneiss at LCW received the score of 10, and the pellitic rocks the score of 5, at MCW, according to the characteristics discussed before. Araújo (2006) reported that since the permeability and transmissivity from these rocks are low, the C horizon plays an important role on water storage. The alluvial areas, with Haplic Gleisol and Fluvic Neosol, as well as wetland at LCW, the scores are 0, because they are in discharge areas. Discharge is generally considered to occur in gentle and topographic lows in humid regions (SCANLON; HEARLY; COOK, 2002), major drainage lines, and break of slopes in low areas (SALAMA et al., 1994). According to Tweed et al. (2006), all regions where groundwater is not discharging to the surface are considered potential of recharge.

Table 4 Scores of soil surface topography, solum depth, and morphology (texture and structure) at LCW

Soil classes (k)[1]	Parent Material	Soil surface	Soil morphology	Solum depth	Land use	Typical value (V^k)
HC1	10	8	6	5	Native forest – 50	79
					Pasture – 10	39
					Regeneration – 40	69
HC2	10	10	4	10	Native forest – 50	84
					Pasture – 10	44
					Regeneration – 40	74
HC3	10	9	4	10	Native forest – 50	83
					Pasture – 10	43
					Regeneration – 40	73
HC4	10	7	5	10	Native forest – 50	82
					Pasture – 10	42
					Regeneration – 40	72

[1]HC: Haplic Cambisol

Table 5 Scores of soil surface topography, solum depth, and morphology (texture and structure) at MCW

Soil classes (k)[1]	Parent material	Soil surface	Soil morphology	Solum depth	Land use	Typical value (V^k)
RL	5	15	10	15	Maize – 15	60
					Eucalyptus – 18	63
					Native forest - 20	65
					Pasture – 13	58
RYL	5	11	8	15	Maize – 15	54
					Eucalyptus – 18	57
					Native forest - 20	59
					Pasture – 13	52
YL	5	13	7	15	Maize – 15	55
					Native forest - 20	60
					Pasture – 13	53
HC	5	8	4	5	Maize – 15	37
					Native Forest - 20	42
					Pasture - 13	40

[1]RL – Red Latosol; RYL – Red-Yellow Latosol; YL – Yellow Latosol; HC – Haplic Cambisol

Topographic gradients control the rate in which soil water moves downslope, thereby determining the portion of stormwater that will be transmitted directly to the channel network (surface runoff) and that will be retained by soil post-event (PRICE, 2011). The relief at MCW is gentle and at LCW is mountainous. This fact explains the general higher scores of surface topography at MCW than LCW, whose rainfall has more opportunity to infiltrate and move downward to groundwater. Locally and in descending order of scores, on summits of MCW, stormwater tends to infiltrate or slowly direct surface runoff, where the Red Latosol are predominant and scored the highest value (15). The lowest slopes, which are closer to the footslope (Yellow Latosol) got the score of 11. From 8 to 20% of slope and predominantly in the intermediate portions of the relief, where the Red-Yellow Latosols are located, the score is also 11. The steepest slopes in the landscape, have the highest potential for direct surface runoff, and hence, are commonly the most eroded, and exhibit the thinnest soil profiles (SCHAETZL; ANDERSON, 2005), like the Inceptisols, which received the score 8.

The highest score (10) at LCW were given to soils located at lower slopes (Haplic Cambisol 2). For the others, the scores accounted for the combination of slope, plan and profile, since the convergent and divergent water-flow, determine localized areas with higher or lower infiltration (SCHAETZL; ANDERSON, 2005). Within the range of 20 to 45% slopes, the convex plan curvature and linear profile curvature received the score of 9 (Haplic Cambisol 3), and the areas with concave plan and profile curvature (Haplic Cambisol 1) scored 8. The lowest score (7) was given for soils located in higher slopes (45-95%), specifically to Haplic Cambisol sites. Tetzlaff and Soulsby (2008) demonstrated that the upper 54% of a large river catchment in Scotland supplied 71% of the river’s base flow and the groundwater of the lower slopes of mountainous headwaters (where colluviums deposits occur) provide a major source of base flow to the river system.

The *solum* depth was obtained from profile description and accounts only to A and B horizons, excluding C horizons. The soils, in the sites studied, were classified as shallow (50 - 100 cm), deep (100 - 200 cm), and very deep (> 200 cm) (EMBRAPA, 2006). Considering the geographical expression of soil classes in each watershed, the main soil depth contrast is between Inceptisols at LCW and Latosols at MCW. The depth, structure, morphology, sulfur attack, physical properties by land use are presented in Table 6 and 7. At MCW, the Latosols are very deep and received the highest scores (15), which mean more opportunity for water storage and infiltration and less surface runoff or lateral movement of water. The Inceptisol is shallow and received a score of 5. There is a predominance of deep Inceptisols at LCW (Haplic Cambisols 2, 3 and 4), which the score is 10. The Haplic Cambisol 1 is shallow and the score is 5.

Table 6 Soil properties at LCW.

Soil classes[1] (k)	*Solum*[1] Depth (cm)	Soil morphology: Structure of B horizon[2]	Soil morphology: Texture[3] (g kg^{-1})	Sulfuric acid attack[4]	Land use (k)	Topsoil physical properties[5]: Ksat (m day^{-1})	OM (%)	Bulk density (g dm^{-3})	Drainable porosity (%)
LCW									
Haplic Cambisol1	0-77 (shallow)	Bi/Cr: moderate, medium/coarse, angular blocky.	Bi/Cr: 340-270-390	Bi/Cr - Al_2O_3: 174.9; Fe_2O_3: 73.7; Ki: 0.94	Native forest	3.49	5.37	0.83	38
					Pasture	1.32	4.67	1.07	21
					Regeneration	1.55	4.90	1.01	26
Haplic Cambisol2	0-130 (deep)	Bi1: weak, medium subangular blocky. Bi2: massive BC: massive	Bi1: 350-100-550 Bi2: 490-110-400 BC: 250-190-560	Bi1 - Al_2O_3: 16.02; Fe_2O_3: 8.75; Ki: 1.62 Bi2 - Al_2O_3: 18.17; Fe_2O_3: 23.08; Ki: 1.54 BC - Al_2O_3: 24.69; Fe_2O_3: 9.79; Ki: 1.98	Native forest	2.30	5.10	0.98	33
					Pasture	0.15	4.17	1.12	19
					Regeneration	1.58	4.30	0.94	27

[1]Solum depth: only A and B horizon was computed, excluding C horizon; very shallow: ≤ 50cm; shallow: > 50 cm ≤ 100 cm; deep: > 100 cm ≤ 200 cm; very deep: > 200 cm. [2]Grade, size, and shape respectively; AB was not included.[3]Clay, silt and sand respectively. [4]Al_2O_3 and Fe_2O_3 in g kg^{-1}; Ki: SiO_2/Al_2O_3. [5]Depth of sampling: 0-15 cm

Table 6, continuation

Soil classes[1] (k)	*Solum*[1] Depth (cm)	Soil morphology: Structure of B horizon[2]	Soil morphology: Texture[3] (g kg^{-1})	Sulfuric acid attack[4]	Land use (k)	Topsoil physical properties[5]: Ksat (m day^{-1})	OM (%)	Bulk density (g dm^{-3})	Drainable porosity (%)
LCW									

Haplic Cambisol3	0-110 (deep)	Bi1: weak, fine to medium, subangular blocky and strong very fine and granular. Bi2: massive BC: weak, fine to coarse, subangular blocky	Bi1: 210-220-570 Bi2: 190-230-580 BC: 180-250-570	Bi1 - Al_2O_3: 9.6; Fe_2O_3: 5.0; Ki: 1.10 Bi2 - Al_2O_3: 11.4; Fe_2O_3: 9.9; Ki: 0.97 BC - Al_2O_3: 12.3; Fe_2O_3: 8.7; Ki: 1.09	Native forest	2.11	5.68	0.89	34
					Pasture	1.69	4.26	1.06	18
					Regeneration	0.92	4.18	1.01	27
Haplic Cambisol4	0-150 (deep)	Bi: weak, fine and subangular blocky	Bi: 570-110-320	Bi - Al_2O^3: 22.0; Fe_2O_3: 12.2; Ki: 1.27	Native forest	2.25	6.26	0.78	38
					Pasture	1.08	3.53	1.18	21
					Regeneration	1.04	3.28	1.15	25

[1]Solum depth: only A and B horizon was computed, excluding C horizon; very shallow: ≤ 50cm; shallow: > 50 cm ≤ 100 cm; deep: > 100 cm ≤ 200 cm; very deep: > 200 cm. [2]Grade, size, and shape respectively; AB was not included.[3]Clay, silt and sand respectively. [4]Al_2O_3 and Fe_2O_3 in g kg^{-1}; Ki: SiO_2/Al_2O_3. [5]Depth of sampling: 0-15 cm

Table 7 Soil properties at MCW

Soil classes (k)	*Solum*[1] Depth (cm)	Soil morphology		Sulfuric acid attack[4]	Land use	Topsoil physical properties			
		Structure of B horizon[2]	Texture (%)[3]			Ksat (m day^{-1})	OM (%)	Bulk density (g dm^{-3})	Drainable porosity (%)
	MCW								

Red Latosol	>200 (very deep)	BA: weak, fine and medium, subangular blocky Bw1: strong, very fine, granular Bw2: strong, very fine, granular	BA: 630-210-160 Bw1: 670-190-140 Bw2: 730-150-120	Bw2 - Al_2O_3: 358; Fe_2O_3: 157; Ki: 0.53	Maize	0.87	3.17	1.13	16
					Eucalyptus	1.72	3.40	1.14	13
					Native forest	0.24	1.60	1.31	10
					Pasture	1.06	3.20	1.12	15
Red-Yellow Latosol	>240 (very deep)	Bw: weak, medium and coarse, subangular blocky.	Bw: 650-150-200	Bw - Al_2O_3: 309; Fe_2O_3: 136; Ki: 0.64	Maize	1.04	2.68	1.01	22
					Eucalyptus	0.98	3.82	1.09	14
					Native forest	0.51	2.52	1.20	12
					Pasture	0.71	2.40	1.12	16

[1]Solum depth: only A and B horizon was computed, excluding C horizon; very shallow: ≤ 50cm; shallow: > 50 cm ≤ 100 cm; deep: > 100 cm ≤ 200 cm; very deep: > 200 cm. [2]Grade, size, and shape respectively; AB was not included.[3]Clay, silt and sand respectively. [4]Al_2O_3 and Fe_2O_3 in g kg^{-1}; Ki: SiO_2/Al_2O_3. [5]Depth of sampling: 0-15 cm

Table 7, continuation

Soil classes (k)	*Solum*[1] Depth (cm)	Soil morphology		Sulfuric acid attack[4]	Land use	Topsoil physical properties			
		Structure of B horizon[2]	Texture (%)[3]			Ksat (m day^{-1})	OM (%)	Bulk density (g dm^{-3})	Drainable porosity (%)

MCW									
Yellow Latosol	>225 (very deep)	Bw1: weak, fine and medium, subangular blocky. Bw2: moderate, medium and coarse, subangular blocky. Bf: massive	Bw1: 670-130-200 Bw2: 640-120-240 Bf: 650-150-200	Bw2 - Al_2O_3: 328; Fe_2O_3: 171; Ki: 0.57	Maize	1.91	2.00	0.96	20
					Native forest	0.78	2.80	1.09	14
					Pasture	0.44	2.65	1.10	16
Haplic Cambisol	0-79 (shallow)	Bi: weak, medium, subangular blocky. BC: weak, medium and coarse, subangular blocky	Bi: 640-180-180 BC: 650-190-160	Bi - Al_2O_3: 268; Fe_2O_3: 118; Ki: 1.28	Maize	0.83	3.28	1.11	19
					Native forest	0.25	3.00	1.11	13
					Pasture	0.68	2.68	1.20	10

[1]Solum depth: only A and B horizon was computed, excluding C horizon; very shallow: ≤ 50cm; shallow: > 50 cm ≤ 100 cm; deep: > 100 cm ≤ 200 cm; very deep: > 200 cm. [2]Grade, size, and shape respectively; AB was not included.[3]Clay, silt and sand respectively. [4]Al_2O_3 and Fe_2O_3 in g kg^{-1}; Ki: SiO_2/Al_2O_3. [5]Depth of sampling: 0-15 cm

The structure and texture were also used to compound typical values. Structure refers to the arrangement of primary soil particles, e.g. sand and clay in natural aggregates. Hydrologic functioning of soils and landscapes are defined by structure of pathways and voids available for water to move and to be stored. In particular, both ecological changes in management are known to alter both soils structure and its hydrologic functioning. Pedology is strong in providing information about structure of soil and soil cover whereas hydrology renders rich information about soil hydrologic functioning (PACHEPSKY; RAWLS; LIN, 2006). In the topsoil, the frequent wetting and drying can be responsible for decreasing aggregate stability (CARON; KAY; STONE, 1992), where the granular structure can behave as a blocky structure, thus decreasing permeability. The lack or low land cover, as provided by the degraded pasture, can worsen this phenomenon.

In the Table 6 and 7 is showed the type of structure, texture and results of sulfuric attack of the B horizon, and topsoil physical properties. Latosol is weathered (low ki values), developed and very deeper, with high values of Fe_2O_3 and Al_2O_3. This soil tends to have better physical properties through the profile than Inceptisols due to higher aggregate stability that allows water movement through the soil (MOTTA; CURI; FRANZMEIER, 2002). Higher aggregate stability of Latosol has been related to Al-oxides (gibbsite) (FERREIRA et al., 1999). Values of Ki <0.75 has been related to gibbisite mineralogy, while values >0.75 indicate caulinitc mineralogy in Latosols (FERREIRA; FERNANDES; CURI, 1999; RESENDE; SANTANA, 1988). At MCW the Latosols showed Ki values <0.64. Gibbisite Latosols have shown lower values of bulk density, higher total porosity, macroposity, and Ksat (CHAGAS et al., 1997; FERREIRA; FERNANDES; CURI, 1999).

Holzhey and Kimble (1986) concluded that water retention curve of well-developed and granular structure Latosols is a typical curve of a clay soil in higher suctions. However, at intermediate suctions, it reflects the low silt content, and at lower suctions there is a characteristic bulge in the curve, reflecting the large number of pores greater than 0.1 mm in diameter. This part of curve, according to Sharma and Uehara (1968), is similar to the one in sandy soils. The hydraulic conductivity is well correlated with pore volume with diameter greater than 0.07 mm. According to Resende (1985) and Resende, Curi and Lani (1999), in Latosols, even with higher clay content, there is a high permeability, due to the small and well-expressed granular structure. Ferreira, Fernandes and Curi (1999) pointed out that higher clay content the higher the soil permeability. Thus, it is possible to conclude that structure in the B horizon of Latosols is more important than texture in determining their hydrologic behavior.

Cambisols follow the opposite trend of Latosols. They have not suffered much weathering and leaching (Ki > 0.94), and the values of Fe_2O_3 and Al_2O_3 are lower. They have high silt content, whereas strongly weathered Latosols usually have low silt content (TOMASELLA; HODNETT; ROSSATO, 2000). The higher silt content and the low permeability and the restrictive permeability of underlying rocks favor the surface runoff and lateral flux, instead of deep water percolation (ARAÚJO, 2006).

Latosols received higher scores than Cambisols due to better structure and permeability in depth. Within MCW, Red Latosols have granular structure and received the higher score (10), followed by RYL with subangular blocky and score of 8, Yellow Latosols with the score of 7, due the massive structure that can decrease the water infiltration, and Haplic Cambisols, which the score is 4. The score of 4 was given to Haplic Cambisols 2 and 3 due to the massive structure. The Haplic Cambisol 1 received the score of 6, whose grade of the aggregate is stronger than others and does not have massive structure, and

Haplic Cambisol 4 received the intermediate score due to higher clay content that can lead a low permeability.

The scores of land use accounted for the role of canopy on rainfall interception that makes the infiltration slower as well as the effect of vegetation on the soil by increasing of organic matter, and improving physical properties. The variance between land uses was statistically significant, which means the physical properties are affected by land use, except for Ksat at MCW (Table 8 and 9). Differently from the other physical properties studied, the Ksat values represent the topsoil depth only; however, this property is also influenced by soil properties at deeper depths, and therefore, it might be influenced by pedological features more than land use features. The good physical properties of Latosols are mainly influenced by aggregate stability. Aggregates of clay (largely kaolinite and gibbsite) are stabilized by high contents of Fe- and Al-oxides, and/or organic matter.

Table 8 Analysis of variance for testing the significance of land use effects on the soil properties at LCW

Soil property	Source of variance	df[1]	Sum of squares	Mean square	F value
Organic matter (%)	Land use effect	3	149.17404	49.72468	11.34**
	Residual	188	842.11467	4.38601	
Bulk density (g cm^{-3})	Land use effect	3	2.74024	0.91341	29.44**
	Residual	188	5.83378	0.03103	
Drainable porosity (mm)	Land use effect	3	2.51321	0.83773	28.51**
	Residual	187	5.49527	0.02938	
Ksat[1] (m day^{-1})	Land use effect	3	97.43730	32.47910	3.67**
	Residual	192	1696.96238	8.83834	

[1]df – degrees of freedom; *Significant at the 0.05 level. ** Significant at the 0.01 level.
[1]Ksat – saturated hydraulic conductivity

Table 9 Analysis of variance for testing the significance of land use effects on the soil properties at MCW

Soil property	Source of variance	df[1]	Sum of squares	Mean square	F value
Organic matter (%)	Land use effect	3	11.52841	3.84280	4.74**
	Residual	158	128.00818	0.81017	
Bulk density (g cm^{-3})	Land use effect	3	0.08183	0.02727	2.72*
	Residual	158	1.58182	0.01001	
Drainable porosity (mm)	Land use effect	3	578.73223	192.91074	4.69**
	Residual	158	6496.18803	41.11511	
Ksat (m day^{-1})	Land use effect	3	0.82612	0.27537	1.03
	Residual	1158	42.1850375 1	0.2669939 1	

[1]df – degrees of freedom; *Significant at the 0.05 level. ** Significant at the 0.01 level.
[1]Ksat – saturated hydraulic conductivity

Summary statistics of soil physical properties for the data stratified into four land uses are listed in Table 10. The mean test did not show one unique trend on land use influence on soil properties, thus the four types of land uses were considered differently as categorical information on soil types, as was pointed out by the F test.

Table 10 Statistics of soil physical properties at LCW and MCW

Land use[1]	Organic matter (%)		Bulk density (g dm^{-3})		Drainable porosity (%)		K sat (m day^{-1})	
	Mean	STD	Mean	STD	Mean	STD	Mean	STD
				LCW				
NF	5.96a	2.13	0.86b	0.20	33.11a	1.52	2.53a	4.15
NR	4.33b	1.86	1.06a	0.15	24.48b	1.38	0.98b	0.94
P	4.14b	2.19	1.12a	0.17	18.33c	1.51	1.20b	2.32
WL	3.77b	1.98	0.99a	0.14	17.70bc	1.36	0.76ab	0.76
				MCW				
NF	2.68a	0.87	1.14b	0.10	13.36b	7.51	0.31a	2.87
P	2.74a	0.88	1.13b	0.09	14.44b	6.31	0.41a	3.33
C	2.96a	0.99	1.08a	0.12	18.75a	6.19	0.48a	3.47
E	3.65b	0.82	1.10b	0.10	14.10b	6.71	0.64a	2.81

[1]Land use: NF – native forest; NR –natural regeneration; P – pasture; WL – wetland; C – maize; E – eucalyptus. [3]STD – standard deviation. Means followed by the same letter do not differ significantly ($p<0.05$)

The structure of topsoil was not accounted in this score, since the granular structure has a behavior of block structure especially in soils with low canopy, as mentioned before. The average values of Ksat, organic matter, bulk density within soils by land uses are in the Table 6 and 7.

Comparing the physical properties, LCW has showed the best physical conditions for promoting infiltration. The Atlantic Forest got the highest score (50), followed by natural regeneration (40) and pasture (10). Soils under forest showed the general trend of higher values of Ksat, organic matter, drainable porosity and lower bulk density. Furthermore, the decayed root channels of the forest trees, or even the living roots, create a zone of high conductivity and encourage the preferential flow in vertical and lateral (downslope) direction (NOGUCHI et al., 1997). Ávila, Mello and Silva (2010) and Mello et al. (2011) analyzed the spatial distribution of soil moisture at LCW and both observed lower fluctuation of soil moisture content throughout the time, meaning greater residence time for water in soil under Atlantic Forest.

Besides the highest values of organic matter and the thick layer of litter (according to field observations), the interception of rainfall by the canopy is still the controlling factor. The opposite behavior happens in soils under pasture, which along with the physiographical conditions make them less favorable to water infiltration and water storage. The dense vegetation plays a role on protect soils from the raindrop impact. The soils with lack or low vegetation cover are likely to form surface sealing, especially Cambisols. Soil surface sealing reduces infiltration rate, decreases water storage in the soil and increase runoff (CASENAVE; VALENTIN, 1992; VALENTIN; BRESSONB, 1992). The predominance of Cambisol under pasture and higher slopes were accounted by the score, whose values were lower to LCW.

The main land use at MCW is pasture with high degree of degradation (ARAÚJO, 2006). It affects physical properties and consequently may decrease the water infiltration. There is only a general trend of better physical properties under maize and eucalyptus (grown with low technical level and without conservationist practices). The Cerrado scored 20. The score of eucalyptus is 18, the maize is 15 and pasture 13.

3.2 Spatial prediction of the recharge potential at MCW and LCW

The sum of scores provided the typical values in Table 4 and 5, which were used to predict the recharge potential, presented in the Figure 3and 4 (a and b). Figures 3 and 4 (b) display the same range of values (from 0 to 84) at both watersheds, in order to make them comparable. And the histograms (Figures 3 and 4 c) show the frequency observed of pixels for the recharge potential values, following the same color scheme of Figures 3 and 4 (c). Figure 3 and 4 (d) show the hardened maps. The indexes of groundwater recharge and the fuzzy membership values were able to distinguish different potentiality of recharge and discharge along the landscape in a continous way. The low values (darker blue color) show the groundwater discharge areas.

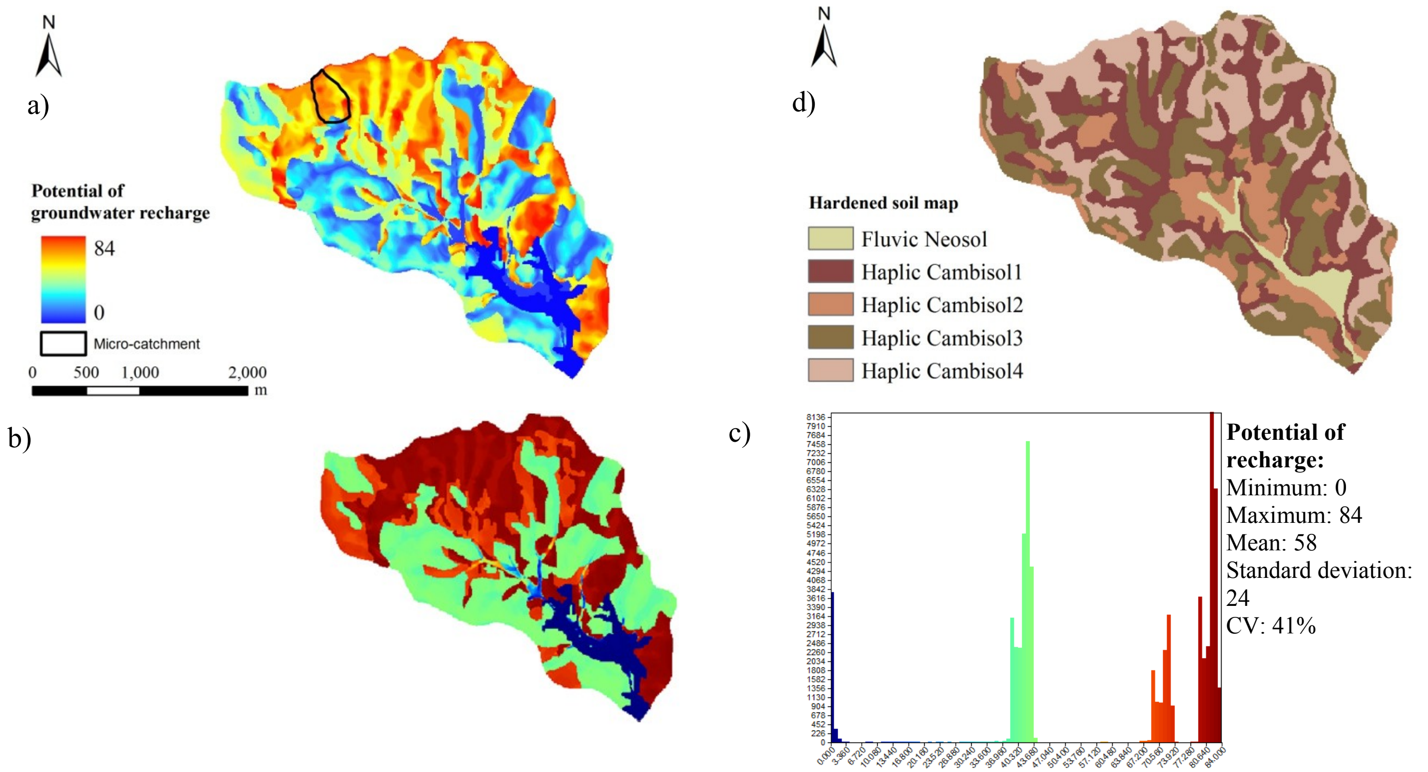

Figure 3 Spatial prediction of the potential of groundwater recharge (a), map with the same range of values at both watersheds (b), it respective histogram (c), and the hardened soil map (d)

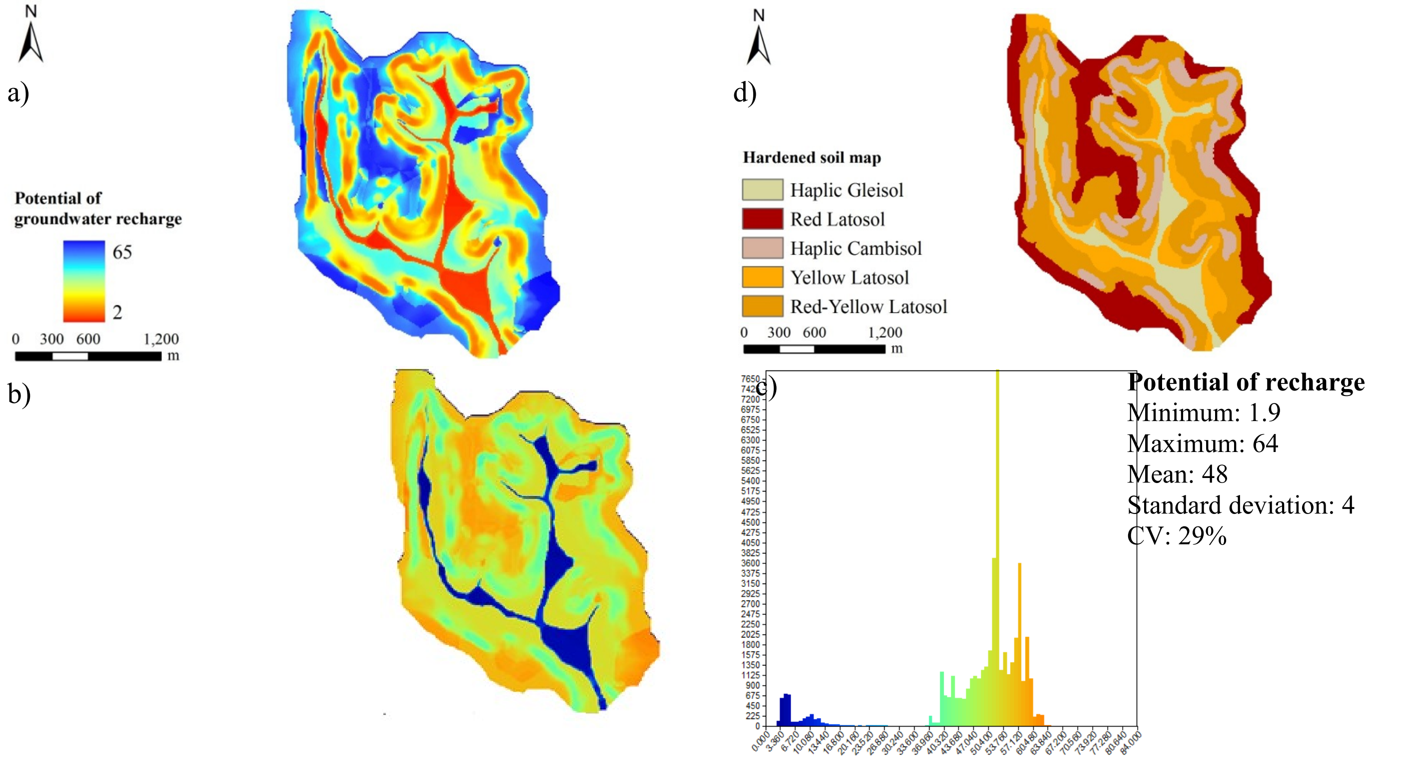

Figure 4 Spatial prediction of the potential of groundwater recharge (a), map with the same range of values at both watersheds (b), it respective histogram (c), and the hardened soil map (d)

Comparing the histograms, LCW has larger frequency of pixels belonging to higher values, which denotes a higher potential of groundwater recharge than MCW. The extreme differences of values between native forest and pasture should be responsible by the higher spatial variability at LCW, characterizing a highest coefficient of variation (CV=41%). MCW showed less spatial variability (lower CV than LCW) with potential of recharge concentrated from 33 to 66.

The highest values of recharge potential at MCW, are in the flat top areas, where there is a predominance of Red Latosols, along the influence of the bedrock, whose inclined orientation of layers enhance the water infiltration. The values around Yellow and Red-Yellow Latosols show the intermediate values. Besides soils with the lowest values in discharge areas, the Inceptisols, showed the lowest potential of discharge at MCW, mainly under pasture. Soils under native forest, eucalyptus or maize showed relatively higher values than pasture.

In the scores chosen, there is a higher contribution of land use at LCW, and higher contribution of soil and landscape features at MCW. Although the topographic gradients control the rate of water infiltration and groundwater recharge, the effect of land use may significantly modify it. The predominance of native forest or natural regeneration surpasses the relief affect, and the values of potential of groundwater recharge are higher at LCW.

So far, all of interpretations were done from a pedologic and geomorphic point of view. This type of analysis should also consider the precipitation regime (average and distribution) that also contributes to groundwater recharge and base flow.

3.3 Hydrologic indicators for assessing the potential of groundwater recharge indexes

In order to validate and better understand the groundwater recharge indexes, some hydrological indicators were analyzed. Table 11 shows the mean depth values of total flow, base flow, direct surface runoff, precipitation and potential evapotranspiration monitored in the period from 2006 to 2010 for LCW and MCW. For MC-LCW, the water balance was obtained only for 2009-2010. The relationships between the base flow and direct surface runoff and total flow, respectively, BF/TF and DR/TF, are also presented. The positive water balance (precipitation greater than evapotranspiration) makes both these regions with respect to water yield, as having high potential for generating base flow, and rising water levels in the rivers downstream the study sites. According to and Mello et al. (2008) and Pinto et al. (2009), who worked with hydrological simulation in these sites, there is no contribution of the geologic aquifer in the base flow during the dry season as inferred from the low values of electric conductivity (< 90 μS cm-1) and little fluctuation of water temperature (from 15 to 20ºC). This way, the flow regime is strongly related to the water balance of the preceding year, to the pedologic and to land use features (MENEZES et al., 2009).

Table 11 Mean hydrological indicators for the MCW, LCW and MC-LCW

Sites	Total flow (mm/ month)	Base flow (mm/ month)	Direct runoff (mm/ month)	Precipitation (mm/ month)	ET (mm/ month)	BF/ TF[1]	DR/ TF[2]
LCW	72.0	53.2	18.8	184.5	112.5	0.7	0.3
MCW	53.4	25.3	28.1	133.4	80.0	0.5	0.5
MC-LCW[3]	64.1	45.3	18.7	143.8[4] (184.5)	116.4	0.7	0.3

[1]BF – baseflow; TF – total flow; [2]DR – direct runoff; [3]Hydrological year of 2009-2010; [4] internal precipitation (precipitation through canopy)

LCW has showed values of precipitation and base flow much higher than MCW and lower values of the direct surface runoff. Base flow depends on the water stored in the aquifer and aquifer transmission. Therefore, higher values of base flow are an indicative of higher direct recharge of the aquifer. The role of Atlantic Forest along with higher precipitation pointed out that LCW has a higher potential for direct recharge of aquifer than MCW.

Considering that the precipitation and evapotranspiration are different between the watersheds, the relative values of base flow or direct surface runoff in relation to the total surface runoff were calculated to make the hydrological indicators comparable or dimensionless. The participation of the base flow in the total flow is higher at LCW, where the values are around 74% with lower contribution of direct surface runoff in the total flow. The forest cover is associated with high infiltration and recharge of basin subsurface storage (PRICE, 2011). In spite of some results in the literature showed that the removal of forest can lead to increasing of the base flow (KEPPELER; ZIEMER, 1990; SMITH, 1991), due to decreasing of interception and evapotranspiration rates, given the surface is not drastically altered (PRICE, 2011), this study showed the opposite. A positive water balance and smaller direct surface runoff increase the recharge reflecting an increase in base flow (CHARLIER et al., 2008). The sites in the Atlantic Forest are in geochemical balance for centuries. And as mentioned before, the higher altitudes are more protected from geological erosion where is possible to find evidences of paleoenvironments from Pleistocene (BIGARELLA; ANDRADE-LIMA; RIEHS, 1975; RESENDE; LANI; REZENDE, 2002).

The accumulation of litter and organic matter in soils under forest contributes to the decrease of the evaporation of water from soil and stores part of rainfall water before getting into the soil (FACELLI; PICKETT, 1991). This situation leads to a slowly water supply to the aquifers, contributing to the base flow during the dry season making it more productive (MENEZES et al., 2009). Another contribution of litter and higher organic values, as showed before, is the improvement of soil physical-hydric properties (higher hydraulic conductivity, drainable porosity and lower bulk density).

Another hypothesis to explain these results is a possible downward subsurface preferential flow path. Siddle et al. (2001) investigated the downslope continuity of a subsurface preferential flow path in a forested hillslope and concluded that not only the individual macropores but also a complex three-dimensional linkage of macropores in the soil and substrate is important in the preferential flow. An important part of the continuum linkage for preferential flow system in forest soils is the existence and spatial distribution of high permeability zones. Such discrete zones include: decaying logs and stumps of dead trees; smaller buried pieces of wood and other organic material; pockets of soil loosened by burrowing animals, or other bioturbations; and mesopores that surround macropores which effectively enlarge these preferential flow paths during wet conditions. Macropores were not measured in the study sites, but features that are common in tropical forest, and also observed in the field, where the thick layer of litter was found under Atlantic Forest or even in natural regeneration (JUNQUEIRA JÚNIOR, 2006), making 54.7% of the land uses suggests the preferential flux as one possible mechanism of downward water movement to the aquifer. Rainwater infiltrating through preferential pathways and macropores causes rapid groundwater recharge, while rainfall exceeding the infiltration capacity yields direct surface runoff (AKSOY; WITTENBERG, 2011).

At MCW, the base flow corresponds to only 47% of the total flow, and there is a higher contribution of direct surface runoff and lower precipitation. The more permanent canopy decreases associated with pasture or agriculture, may decrease baseflows due to soil compaction, reduction of soil organic matter, and increase in surface sealing (PRICE; JACKSON; PARKER, 2010; WOLTEMADE, 2010; ZIMMERMANN; ELSENBEER; MORAES, 2006). Besides, we could observe more concentrated rainfall during the summer season producing some intense rainfall events in MCW and consequently, more direct surface runoff. Although the rainfall is concentrated in summer, like at MCW, there are much more rainfall events during the dry season at LCW, and according to Ávila (2008) and Mello et al. (2011), these events contribute to the maintenance of water stored in soil profile and as a result, the recharge process begins earlier at LCW due to greater initial soil moisture.

Figure 5 shows the behavior of hydrograph in sites between August/2006 and September/2010, completing four hydrologic years and the same for MC-LCW but for August/2009-September/2010. We can see the behavior of the base flow in relation to the total flow and respective rainfall, in monthly interval. The coefficients of recession (α) of the base flow for each hydrologic year are also presented.

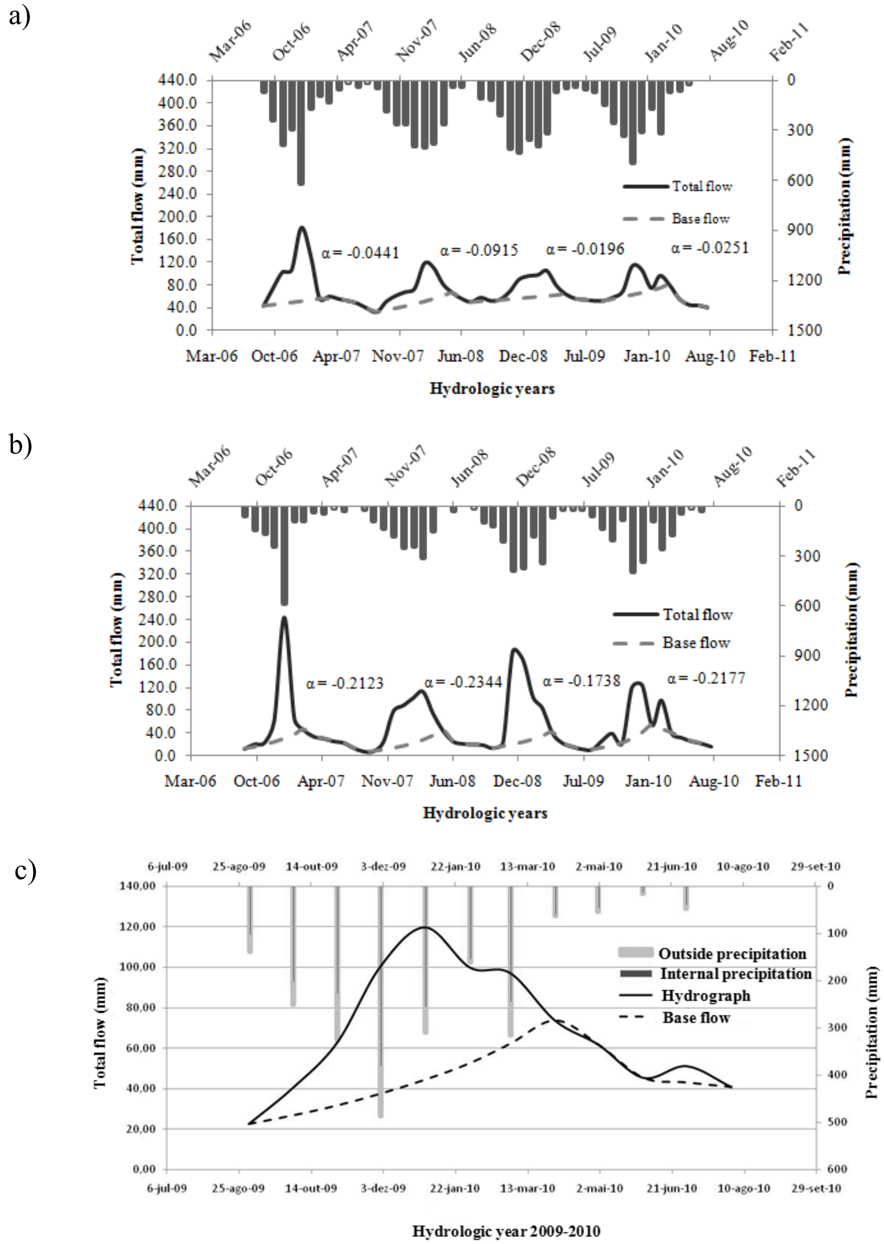

Figure 5 Monthly behavior of total flow, base flow and precipitation throughout four hydrological years at LCW (a) and MCW (b) and, behavior of water balance in a micro-catchment occupied by Atlantic Forest belongs to LCW (MC-LCW) during 2009-2010 hydrological year (c)

Besides higher mean monthly precipitation, there are more events throughout the years and the intra-annual variability of rainfall regime is less felt at LCW. The responses to rainfall begin quickly since there is more moisture in soils occupied by Atlantic Forest, according to Mello et al. (2011). However, the base flow occurs in response to the rainfall season and direct recharge. The rainy season is extremely important to promote shallow aquifer recharge and consequently, to provide base flow during the winter period (driest part of the year) at both watersheds.

At LCW, the base flow curves were always higher than at MCW during the rainy season, with lower direct surface runoff (difference between total and base flow). We can observe in Figure 5 that the hydrological year of 2006-2007 was atypical in both sites due to influence of La-Niña phenomena. However, in MCW, the dry period was more pronounced and there was not any significant rainfall event between May and September, resulting in a base flow only about 8.5 mm in the end of hydrological year. In this period, at LCW, also a more pronounced recession occurred during the monitoring period but this behavior was much less felt in relation to the MCW, with the value for the base flow about 32 mm. In opposite of MCW, we can observe some rainfall events in the period mentioned and therefore, better conditions to the base flow.

MCW has showed more fluctuations between the total and the base flow, with more pronounced peaks. It can be ascribed by the predominance of extensive pasture as a land use and all of the implications already discussed before.

The rate of discharge from the superficial aquifer is indicated by the slope of the subsequent recession curve and it reflects on the recession coefficient (α). The recession curve means in a general way about the natural storages feeding to the stream (TALLAKSEN, 1995). Although MCW has less annual precipitation (1,500 mm), along with land use features that can reduce the soil water infiltration capacity and consequently, affecting groundwater recharge, this watershed has lower coefficient of recession (around -0.21 in average). It means that the depletion curves of the base flow are smoother, and the residence time of water in the aquifer is higher than at LCW, with water being drained slowly. The lowest coefficient values can suggest more transmissivity of aquifer and higher water storage capacity of very deep soils (Latosols), their subsurface characteristics and smoother relief at this watershed. Considering that a greater water storage capacity and a good structure that promotes soil infiltration makes the Latosols drier, the drainage groundwater pattern is different from a saturated soil (Inceptisols are shallower and become saturated faster than the Latosols). The lithitic contact is far from the surface at MCW. Thus, the role of the regolith also might be contributing to higher water storage (CETEC, 1993).

The water balance of a MC-LCW (16 ha), entirely occupied by Atlantic Forest, is also presented in figure 5c. We can observe some important hydrological features in this environment. The precipitation outside of the watershed was about 2,026 mm and inside as monitored by 25 pluviometers, was 1,622 mm, demonstrating the role of forest on the rainfall interception. Another characteristic is associated with the long process of recharge in this environment. It begins practically with the beginning of hydrological year (September) since, according to Mello et al. (2011), the soil moisture remains over the dry period. This process continues until April. Specifically for this hydrological year, the base flow was about 550 mm while the total flow was about 810 mm, meaning that almost 70% of total flow is compounded by the base flow. Evaluating the Figure 3 (a) and the localization of the micro-catchment MC-LCW, is possible to see the entire catchment with higher values of index, proving it validation as well as the methodology used.

The hydrological indicators pointed out the role of Atlantic Forest acting as a buffer between rainfall and surface runoff, promoting more water infiltration, along with more precipitation and consequently, more water for aquifer recharge and then, more base flow. MCW has showed less potentiality of groundwater recharge due to land use, which is mostly pasture without any conservationist practices or conventional maize crops. Comparing the geomorphic features, MCW has the main conditions to promote the groundwater recharge, but the role of land use surpasses it leading to a low groundwater recharge. Again, the precipitation regime (less annual precipitation) should be considered since the intra-annual pluvial regime is a typical characteristic of region and Campos das Vertentes region is more influenced than Mantiqueira Range region. On the other hand, geomorphic features conditioned the highest time of residence of water in the aquifer, as pointed out by the recession coefficients. Thus, the spatial prediction recharge and hydrologic indicators accounted for these important differences between watersheds.

4 CONCLUSIONS

As long as the prediction of the potential of recharge is in agreement with the knowledge of soils and hydrologic indicators, this method is useful and can help the decision makers and promote a sustainability of the water resources.

The index of potentiality of aquifer recharge, the fuzzy membership values and the vector of similarity showed to be useful for mapping the potential of recharge in a continuous way, accounting to a complex interaction among soils, landscape and land use features.

The prediction maps as well as hydrological indicators pointed out that LCW has the higher potentiality of groundwater recharge, due to the Atlantic Forest and the precipitation regime. Even though the geomorphic characteristics at MCW are more favorable for groundwater recharge, the predominance of pasture along with the precipitation regime, were responsible for the lower potentiality of groundwater recharge.

Since the baseflow can be considered as the outflow of the groundwater reservoir feeding the rivers during dry period, making them more perennial, in order to increase the water yield for public use, the maintenance of Atlantic Forest at LCW, or the use of conservationist practices at MCW are recommended.

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