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UNIVERSIDADE ESTADUAL DE CAMPINAS
Instituto de Geociências
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AVALIAÇÕES E PROPOSTAS PARA O MÉTODO DE MAPEAMENTO DE PERIGO A FLUXO DE DETRITOS DO PROJETO GIDES

Dissertação de mestrado

EVALUATIONS AND PROPOSALS FOR THE DEBRIS FLOWS HAZARD MAPPING METHOD OF THE GIDES PROJECT

CAMPINAS
2018

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AVALIAÇÕES E PROPOSTAS PARA O MÉTODO DE MAPEAMENTO DE PERIGO A FLUXO DE DETRITOS DO PROJETO GIDES

DISSERTAÇÃO APRESENTADA AO INSTITUTO DE GEOCIÊNCIAS DA UNIVERSIDADE ESTADUAL DE CAMPINAS PARA OBTENÇÃO DO TÍTULO DE MESTRE EM GEOCIÊNCIAS NO PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

ORIENTADOR: PROF. DR. JEFFERSON DE LIMA PICANÇO

ESTE EXEMPLAR CORRESPONDE À VERSÃO DA DISSERTAÇÃO A SER DEFENDIDA PELO ALUNO GABRIEL GUIMARÃES FACURI E ORIENTADA PELO PROF. DR. JEFFERSON DE LIMA PICANÇO

CAMPINAS
2018

BIOGRAFIA

Gabriel Guimarães Facuri se formou em geologia pela Universidade Estadual de Campinas e apresenta experiência em diversas áreas de atuação das Geociências. Quando ainda graduando morou nos EUA por duas vezes como intercambista. Também neste período fez estágio supervisionado no *Instituto Costarricense de Electricidad* na Costa Rica, onde trabalhou com mapeamento geológico em terrenos recentes, mapeamento de riscos vulcânicos, de suscetibilidade a movimentos de massa e vulcanoestratigráfico, além de estudos geotérmicos e de monitoramento de sísmica e vulcanismo ativos.

Estagiou na mineração, no setor de agregados para a construção civil ajudando a gerenciar as reservas minerais da rede de pedreiras Basalto, lidando com instituições como CETESB e DNPM, gerindo resíduos e mapeando suas minas. Foi um dos responsáveis pela implantação do *geodatabase* da empresa.

Ainda no setor mineral, mas depois de graduado, trabalhou na pesquisa mineral de ouro pela *Yamana Gold* com exploração *greenfield* em Goiás e *brownfield* e *near mine* no Mato Grosso que também incluíram trabalhos com mapeamento geológico e locação, acompanhamento e descrição de sondagens. Responsável pela gestão de equipes de sondagem e de amostragem de solo e de rocha.

Atualmente trabalha novamente com mapeamento de suscetibilidade a movimentos gravitacionais de massa e inundações e setorização de riscos geológico em vários estados do país pelo Serviço Geológico do Brasil - CPRM de São Paulo.

O primeiro ano de mestrado ocorreu junto a trabalhos praticamente normais na CPRM. Já o segundo houve atenção total e exclusiva às pesquisas de pós-graduação, inclusive com trabalho de campo na área de estudos durante março de 2018 para reconhecer a área e gerar amostras que foram ensaiadas na FEC-Unicamp. Durante as pesquisas de mestrado e a produção deste trabalho foram cursadas disciplinas na Unicamp e na USP, além de um curso no IPH-UFRGS.

Também foi feito um intercâmbio na *Alma Mater Studiorum - Università di Bologna*, Itália. Lá conheceu os trabalhos realizados pelas equipes de monitoramento de movimentos gravitacionais de massa na região dos Dolomitos e zona leste dos Alpes italianos. Além disso, trabalhou no uso e adaptação de um novo método de mapeamento de suscetibilidade a fluxo de detritos com pesquisadores do *Istituto di Ricerca per la Protezione Idrogeologica*, Padova, Itália.

Dedico este a todos os contribuintes paulistas

e brasileiros que tornaram esta pesquisa possível

e aos moradores da comunidade Floresta que sofreram

e ainda sofrem com os efeitos do desastre de março de 2011.

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“Quem quer pega e faz”

Monticelli A. M. M., 2017

RESUMO

AVALIAÇÕES E PROPOSTAS PARA O MÉTODO DE MAPEAMENTO DE PERIGO A FLUXO DE DETRITOS DO PROJETO GIDES

Nos dias 11 e 12 de março de 2011 um evento pluviométrico de grandes proporções causou inundações e milhares de movimentos gravitacionais de massa que acarretaram mortes e muitos prejuízos materiais nos municípios de Antonina, Morretes e Paranaguá, no litoral do Paraná. Este trabalho foca nos grandes fluxos de detritos que atingiram a bacia do rio Jacareí e os usa para testar a nova técnica de mapeamento de perigo proposta pelo Projeto GIDES. A intenção é verificar se há concordância entre o que é previsto pelo mapa e a realidade vista em 2011. Além disso, também se sugere aperfeiçoamentos ao método proposto. O Projeto GIDES é uma parceria de transferência de tecnologia na gestão e prevenção de desastres naturais entre os governos do Brasil e Japão. Embora simples e rápido, o método não mostrou resultados condizentes com a realidade quando feito em sua forma original. Porém depois de adaptações ao caso estudado grandes melhorias puderam ser notadas. Após a divisão do evento em três áreas diferentes baseando-se no processo dominante, os resultados para duas delas se mostraram promissores. Para a área de transporte do fluxo de detritos concluiu-se que a relação que produziu mapas mais próximos ao evento estudado foi a relação entre a altura máxima que o fluxo atingiu com a declividade máxima do canal para cada seção dele. Para a região de deposição de matacões não foi achada nenhuma relação morfométrica satisfatória. Entretanto, para a área de depósito de matérias finos ou menos densos a mudança mais significativa foi a incorporação também das declividades de 0 a 2° no mapeamento. Na avaliação de bacias para serem mapeadas, os pré-requisitos do método do Projeto GIDES não se encaixaram ao caso estudado. Por isso, foi empregado o método usado pelo IPT/CPRM com algumas sugestões e incrementos. Este procedimento foi capaz de separar as bacias sujeitas a fluxos de detritos das não sujeitas com acerto perfeito. Para as duas técnicas usadas, dezenas de índices e atributos morfométricos da drenagem, das encostas e da bacia foram testados e confrontados com o intuito que pudessem ser utilizados para que resultados verdadeiros positivos ficassem maiores e falsos negativos e positivos ficassem proporcionalmente menores. Após toda a análise, foram obtidos valores e equações que podem ser usados inicialmente na análise de outras bacias com certa semelhança a deste estudo para se mapear o perigo a fluxos de detritos, embora uma validação em outros locais ainda é necessária. Estas diferentes técnicas adaptadas à realidade local (e talvez também da Serra do Mar como um todo) podem ser usadas separadamente ou em conjunto para criar tais mapas de forma mais rápida, simples, barata e confiável utilizando dados de entrada que podem ser relativamente fáceis de adquirir.

Palavras-chave: fluxo de detritos, mapeamento de perigo, rio Jacareí, morfometria de bacia.

ABSTRACT

EVALUATIONS AND PROPOSALS FOR THE DEBRIS FLOWS HAZARD MAPPING METHOD OF THE GIDES PROJECT

On March 11th and 12th, 2011, a large rainfall event triggered floods and thousands of gravitational mass movements that caused deaths and material damages in the municipalities of Antonina, Morretes and Paranaguá, on the coast of Paraná. This work focuses on the large debris flows that have reached the Jacareí river basin and uses them to test the new hazard mapping method proposed by the GIDES Project. The intention is to verify if there is agreement between what is forecasted by the map and the reality seen in 2011. In addition, improvements to the proposed method are suggested. The GIDES Project is a technology transfer partnership on natural disasters management and prevention between the governments of Brazil and Japan. Although simple and fast, the proposed method did not show results consistent with the reality when applied in its original form. However, after adaptations to the studied case, major improvements could be noticed. After dividing the event into three different areas based on the dominant process, the results for two of them proved to be promising. For the debris flow transportation area it was concluded that the relation that produced maps closer to the reality of the studied event was the relation between the maximum height reached by the flow with the maximum channel slope for each channel section. No satisfactory morphometric relationship was found for the boulders deposition region. But for the area of fine or less dense materials deposit, the most significant change was the incorporation of slopes from 0 to 2° in the mapping procedure. In the evaluation of basins to be mapped, the prerequisites of the GIDES Project method did not fit the studied case. Therefore, the method used by IPT/CPRM was employed with some suggestions and increments. This procedure was able to separate the basins prone to debris flows from the non-prone with perfect adjustment. For the two techniques used, dozens of morphometric attributes and indexes of the drainages, slopes and basins were tested and compared so that true positive results could be larger and false negatives and positives would be proportionally smaller. After the analysis, values and equations were determined that could be used initially in the analysis of other basins with some similarity with the studied area to map the debris flow susceptibility, although a validation in other places is still needed. These different techniques adapted to the local reality (and perhaps also to the entire Serra do Mar) can be used separately or together to create faster, simpler, cheaper and reliable maps using relatively easy to find input data.

Keywords: debris flow, hazard mapping, Jacareí river, basin morphometry.

SUMÁRIO

1. INTRODUÇÃO

Os fluxos de detritos são uma das mais perigosas formas de escorregamento, pois são fluxos muito rápidos de material detrítico que descem com muita energia por gravidade em canais profundos atingindo grande mobilidade e podem chegar a carregar até enormes matacões métricos (Hungr et al., 2014). Boa parte das mortes por movimentos de massa em escala mundial se deve aos fluxos de detritos e sua contraparte vulcânica, os *lahars* (Jakob & Hungr, 2005).

O aumento de desastres com ocorrência de fluxos de detritos que aconteceram no Brasil em anos recentes tem levado a um interesse maior no estudo destes fenômenos (Kobiyama & Michel, 2014; Gramani, 2015). Alguns eventos mais antigos são bem conhecidos do público em geral, como os eventos de Caraguatatuba/SP (Costa Nunes e Hunt, 1979), Tubarão/SC (Bigarella et al., 1975), Ubatuba/SP (Augusto Filho, 1993) Três Forquilhas/RS (Potter et al., 2013) e rios Quitite e Papagaio/RJ (Fernandes et al., 2004), além das recentes ocorrências de fluxos de detritos em Petrópolis/RJ que foram descritas por Dourado et al. (2012) e as de Nova Friburgo/RJ por Coelho Neto et al. (2009) e Avelar et al. (2011).

Um evento menos lembrado nacionalmente pela população é o dos fluxos de detrito do litoral do Estado do Paraná em 2011 (**Figura 5** e **9**). Porém, em conjunto com os outros eventos deste mesmo ano, eles foram divisores de água porque geraram muitas indagações públicas e políticas, juntamente com um maior interesse científico neste tipo de movimento de massa. Segundo dados da Coordenadoria Estadual de Proteção e Defesa Civil do Paraná (2011), nos dias 11 e 12 de março daquele ano houve o registro de diversos movimentos gravitacionais de massa e inundações que causaram duas mortes e 200 feridos no município de Antonina/PR, um óbito e 21 feridos em Morretes/PR e mais de dois mil desabrigados. Além disso, os prejuízos materiais dessas duas cidades juntamente com Guaratuba e Paranaguá foram de mais de cem milhões de reais por conta da destruição ou comprometimento de lavouras, equipamentos públicos e privados, entre outras perdas. Antonina e Morretes declararam estado de calamidade pública e Paranaguá decretou emergência, mostrando que o desastre teve proporções estaduais.

Os processos deste desastre foram causados por chuvas de grande volume concentradas em apenas alguns dias. Segundo dados de Picanço e Nunes (2013), nos primeiros dias de março de 2011 foram registrados mais de 600 mm de chuva até a data dos eventos em algumas estações pluviométricas da região afetada. Contudo, a média histórica para o mês inteiro de março é de menos da metade deste valor.

Um importante recurso para evitar perdas maiores nestes tipos de desastre é o entender onde eles podem ocorrer e até onde podem alcançar. Para isso o mapeamento de suscetibilidade a fluxos de detritos é fundamental (Rogelis & Werner, 2014). Porém, a falta de um método padrão de mapeamento a nível nacional causa dificuldades na comparação, tratamento e compilação dos diversos mapas e dados gerados. Dessa forma, faz-se necessário o estabelecimento de procedimentos básicos baseados em parâmetros físicos, que possam nortear os mapeamentos futuros e reduzir as diferenças entre eles, sem que se percam os avanços obtidos regionalmente (CPRM, 2018). Assim, políticas públicas de gestão de riscos naturais e pesquisas científicas seriam muito mais efetivas.

Apesar das pesquisas sobre fluxos de detritos terem se iniciado timidamente ainda no século XIX, foi a partir da década de 1950 e mais intensivamente 1970 que elas ganharam mais peso. Porém, apesar de tantos anos de avanço do conhecimento nesta área, ainda não se pode prever com confiança e exatidão a probabilidade, magnitude e localização dos depósitos dos fluxos de detritos (Jakob et al., 2016).

Um novo procedimento está sendo criado desde 2013 para propor um procedimento padrão de mapeamento de perigo e risco a movimentos gravitacionais de massa elaborado dentro do escopo do Projeto GIDES (Projeto de Fortalecimento da Estratégia Nacional de Gestão Integrada de Riscos e Desastres Naturais). Trata-se é um trabalho conjunto do governo brasileiro e japonês que está sendo desenvolvido, entre outros objetivos, para criar uma técnica padrão de ampla aplicação em todo o território nacional. Este fato traz muita responsabilidade ao projeto que precisa ser comprovadamente eficaz e coerente. Pela importância que este plano pode apresentar ao Brasil, este trabalho propõe-se a testar e validar o método desenvolvido pelo Projeto GIDES de forma que se torne mais assertivo e confiável para o gerenciamento de risco para fluxos de detritos através do mapeamento.

1.1. OBJETIVOS

O principal objetivo é realizar testes de mapeamento de perigo a fluxo de detritos do método proposto pelo Projeto GIDES na região estudada, bem como realizar a validação crítica do método através da análise dos mapas criados a partir dele. Além de testar o procedimento, também se propõe a sugestão de melhorias através de parâmetros morfométricos da bacia, do canal ou de outros métodos. Estes mapas seriam criados unicamente a partir manual do Projeto GIDES, como um usuário comum.

1.2. ESTRUTURA DA DISSERTAÇÃO

Este trabalho apresenta-se em formato alternativo, de acordo com o Art. 2° do Informativo da Comissão Central de Pós-Graduação da UNICAMP (nº 001/2015). O Capítulo 1 é uma introdução que aborda conceitos gerais sobre o fenômeno pesquisado e seu mapeamento, o método do Projeto GIDES, a região de estudos e os objetivos.

Os resultados obtidos na aplicação da técnica de mapeamento do Projeto GIDES, sua validação e sugestões, além das discussões e conclusões são apresentados no Capítulo 2. Ele foi feito no formato de artigo onde são apresentados os resultados e análises dos mapas feitos. O texto ainda não foi submetido à publicação, pois os autores estão esperando as contribuições que certamente virão da banca examinadora.

Uma vez que o tema é comum, algumas superposições entre os capítulos são inevitáveis mesmo tratando o tema sob aspectos e aprofundamentos diferentes. Além disso, ocorrerão também complementações sobre o mesmo assunto entre eles.

1.3. FLUXOS DE DETRITOS

Quando se fala em movimentos de massa é importante ter em mente que eles são compostos por muitos tipos e subtipos. Os movimentos do tipo fluxo podem ser divididos a depender do seu conteúdo de água, sedimentos finos e grossos.

De acordo com Cascini et al. (2014), de forma geral os movimentos de massa do tipo fluxo ocorrem quando na entrada do canal (comumente em drenagens das ordens 0 ou 1) a velocidade dos sedimentos vindos de escorregamentos marginais aumenta principalmente pela junção de duas ou mais massas de propagação. Este aumento de velocidade é devido ao fornecimento de grande quantidade de água de fortes tempestades e do próprio canal para os sedimentos ao longo do caminho, junto com a abundância de material disponível do próprio leito. No final do canal a massa pode parar ou se propagar mais em uma direção desconhecida e/ou a bifurcação de massa pode ocorrer ao longo de ramificações secundárias com diferentes distâncias de saída. Quando o ângulo de inclinação diminui a deposição ocorre onde o canal termina.

Os tipos de fluxos considerados neste estudo são hiperconcentrados ou de enchente (*debris floods* em inglês) e de detrito (*debris flows* em inglês), embora o mapeamento do Projeto GIDES somente trate, *a priori*, do último deles. Eles têm muitas características em comum como o caminho que podem percorrer, uma vez que todos ocorrem inicialmente canalizados nas drenagens de menor ordem. Além disso, sua velocidade também é muito alta porque se iniciam em áreas íngremes e com alto gradiente topográfico (Hunger et al., 2001; Pierson, 2005; Rogelis and Werner, 2014). A diferença entre eles se dá principalmente pelo tamanho e volume (proporcional e total) dos sedimentos, quantidade de água e a morfologia do terreno. Pode-se considerar que a combinação entre estes fatores muda o tipo de fluxo estudado (Cascini et al. 2014).

Os **fluxos hiperconcentrados** ou **de enchente** por sua vez ocorrem também canalizados em velocidades muito altas de água fortemente carregada de detritos (**Figuras 1a** e **6d**). São desencadeados quando o material de deslizamentos de massa atinge o fluxo de água durante inundações extremas em canais íngremes (Hungr et al., 2014). Normalmente, os fluxos de enchente têm a descarga de pico limitada a no máximo de 2 a 3 vezes a de uma grande inundação de água, resultando em um potencial destrutivo localizado devido a um impacto relativamente restrito e profundidade de fluxo relativamente baixa (Jakob & Hungr, 2005).

Finalmente, os **fluxos de detrito** se originam também de uma série de escorregamentos majoritariamente planares e avalanches de detritos (muitas vezes regolitos) que chegam às drenagens de primeiro grau em locais de elevada declividade (**Figuras 1b** e **6c**). Eles conseguem mobilizar depósitos detríticos no leito e nas margens do canal, pois com elevada disponibilidade hídrica até partículas mais grossas se liquefazem ou pelo menos tem um aumento significativo de poro pressão (Frey et al., 2016; Hungr, 2005 e Hungr et al., 2014).

Embora haja diversas denominações, estes detritos presentes no fluxo são, texturalmente, uma mistura de tudo: areia, cascalho, seixos, blocos e até matacões com porções de silte e argila (Hungr et al., 2014), sem esquecer que a grande energia dos fluxos de detritos é capaz de mobilizar quase qualquer material que esteja em seu caminho, inclusive árvores, carros e animais grandes. Isto é possível porque praticamente não há seleção granulométrica em condições com extrema disponibilidade hídrica e de sedimentos que também vêm da erosão acelerada das margens e do fundo do canal somado à entrada de material vinda dos escorregamentos de solo e rocha, rolamentos e quedas de blocos que fluem em velocidades rápidas a extremamente rápidas (Hungr, 2005).

O fluxo de detritos pode ser dividido considerando seus diversos comportamentos e composição. Os detritos grosseiros acumulam-se nas frentes das ondas, como blocos, matacões e troncos, movendo-se para frente, principalmente por deslizamento e rotação, em vez de fluir propriamente como fluxo. Logo atrás há um corpo de detritos saturado em água que parece fluir mais como uma massa liquefeita composta por grãos mais finos do que os detritos frontais (Iverson, 2003; Ujueta & Mojica, 1985).

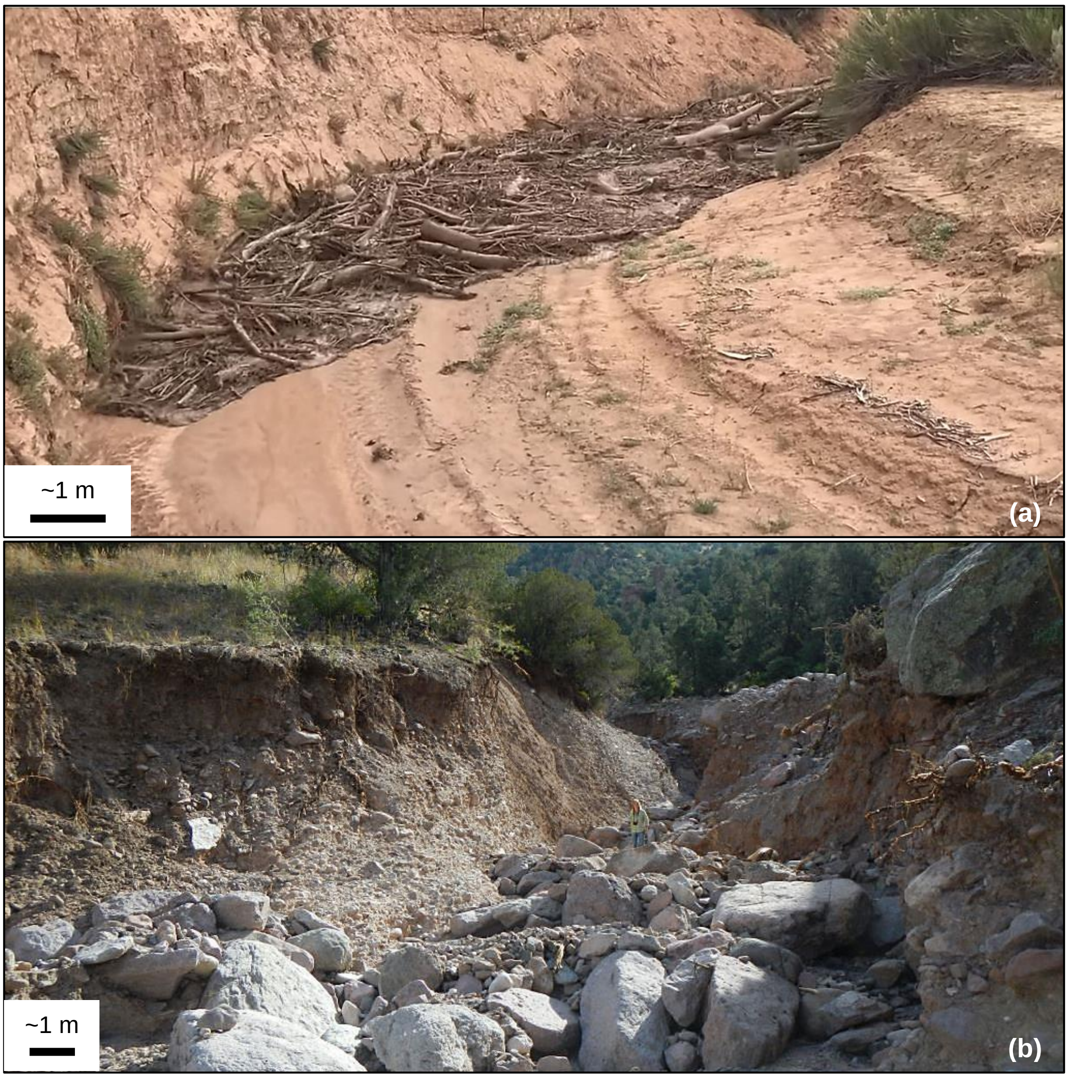

Figura 1 – **(a)** Fluxo hiperconcentrado ou de enchente no Cânion Johnson, EUA (foto retirada de vídeo do site https://youtu.be/ORJtxkuD62E). **(b)** Canal de fluxo de detritos e seu depósito de grandes matacões no Cânion Whitewater, EUA (foto do site do Serviço Geológico Americano – USGS)**.**

Os fluxos de detritos são perigosos também porque eles podem atingir grandes distâncias e volumes, pois são autoalimentados. Uma ou mais frentes do fluxo de detritos são canalizadas e lateralmente erodem as encostas íngremes, produzindo deslizamentos de terra e, assim, adicionando mais sedimentos ao fluxo. Além disso, diques laterais formam-se mais comumente onde os detritos escapam do confinamento lateral por canais de aberturas ou pela descarga em leques ou planícies aluviais (Iverson, 2003).

A magnitude dos fluxos de detritos depende das características do canal, da bacia de drenagem e do processo desencadeador (geralmente eventos de chuva intensa e/ou de longa duração). Mas seu pico de descarga é pelo menos três vezes maior que o de um grande fluxo de inundação de água (Hungr et al., 2014), trazendo grande potencial de destruição.

Uma característica importante destacada por Frey et al. (2016) é que várias testemunhas relataram a secagem do leito do rio antes do evento de fluxo de detritos; alguns até disseram que o rio secava entre pulsos do fluxo, indicando um bloqueio temporal do rio a montante. Isso pode ser causado por pequenos bloqueios de curta duração ou por escorregamentos causados pela forte erosão lateral durante o evento.

Embora possa talvez não parecer, mas é importante notar que os fluxos citados acima não devem ser tratados de forma isolada entre si. É recomendável considerar que muitos eventos podem ter mais de um tipo de fluxo ou haver a transformação em outro tipo após mudanças em seu nível de água e sedimentos finos ou grosseiros ao longo do caminho (Pierson, 2005).

É importante diferenciar o fluxo de detritos e de enchente, pois o primeiro pode ter uma descarga máxima até 20 vezes maior do que as inundações comuns e, portanto, os potenciais de danos são muito diferentes, levando a uma estratégia muito diferente para projetar estruturas de proteção e mapear sua suscetibilidade (Wilford et al., 2004 e Hungr et al., 2014). A maioria das pesquisas e mapas se concentra nos fluxos de detritos porque os de enchente geralmente não desenvolvem forças de alto impacto, sendo que o dano potencial a estruturas é limitado, pois elas carregam menos partículas grandes responsáveis pelos danos causados por impacto e as velocidades de fluxo são mais baixas (Rogelis e Werner, 2014). Entretanto, embora os fluxos de detritos sejam limitados a pequenas drenagens íngremes, fluxos de enchente ou hiperconcentrados podem ocorrer em bacias hidrográficas muito maiores e com maiores descargas, também chamadas de enxurradas (*flash floods* em inglês) sendo ampliadas por cargas pesadas de sedimentos. Os depósitos dos fluxos de enchente estendem-se ainda mais além do que aqueles dos fluxos de detritos e depositam-se em ângulos de inclinação menores. Este fato e a periodicidade de ocorrência no mesmo local influenciam a metodologia dos estudos de mapeamento (Hungr et al., 2014).

Segundo Pierson (2005) a transformação de fluxos hiperconcentrados ou de enchentes para fluxos de detritos e vice-versa acontece e é basicamente dependente do volume total e da quantidade de argila. Adicionalmente Wilford et al. (2004) também mostram que a concentração de sedimentos entre inundações comuns e fluxos de detritos é de 20% e 47%, respectivamente. Ou seja, são valores factíveis de serem atingidos em diferentes momentos durante grandes e complexos eventos pluviométricos e sedimentológicos.

Hungr et al. (2014) ainda citam o desastre de janeiro de 2011 na região serrana do Rio de Janeiro como um exemplo de caso onde mais de 3.500 escorregamentos ocorreram, parte gerando fluxos de detritos em drenagens menores e mais declivosas e fluxos de enchente ou hiperconcentrados em rios maiores. Os autores ainda deixam claro que bacias que geram fluxos de detritos podem também produzir fluxos de enchentes a depender das condições de disponibilidade de água e material detrítico. Por isso muitos depósitos acumulam sedimentos de fluxos de detritos, de enchente e de aluviões normais.

Entender criticamente estes conceitos e tentar avançar no estudo da previsão de comportamento e de locais de impacto do fluxo é de suma importância para a aplicação de diferentes métodos de mapeamento de suscetibilidade ou perigo na área de estudos usando novas técnicas como a do Projeto GIDES.

1.4. PROJETO GIDES

Os anos de 2010 e 2011 foram marcos para o governo brasileiro, pois foi quando ocorreram diversos movimentos de massa de grandes proporções que resultaram em desastres que retiraram a vida de muitas pessoas. A partir disso procurou-se regulamentar e gerenciar melhor a ocupação urbana no país através de diversas ações legais (CPRM, 2013). Foram então criados diversos instrumentos legais relacionados a uma política nacional de proteção, defesa civil e prevenção de desastres. O mais importante deles foi a Lei Federal nº 12.608/2012, que instituiu diversas políticas nacionais para o gerenciamento de riscos de desastres com a criação de órgãos e programas específicos (CPRM, 2013).

A CPRM (Serviço Geológico do Brasil) ficou então encarregada pela setorização emergencial das áreas de risco alto e muito alto no país, elaboração de cartas de suscetibilidade natural e cartas geotécnicas de aptidão urbana. Todos estes trabalhos estão relacionados a movimentos de massa e inundação num contexto em que diversos órgãos foram criados e ações tomadas para que a população ficasse mais segura frente aos desastres naturais.

Como outra consequência destes trabalhos, em 2013 foi firmada uma parceria entre os governos do Japão, através da Agência de Cooperação Internacional do Japão (JICA) e Brasil, representado pelos Ministérios das Cidades, da Ciência, Tecnologia e Inovação, da Integração Nacional e de Minas e Energia. Deste acordo surgiu o Projeto de Fortalecimento da Estratégia Nacional de Gestão Integrada de Riscos e Desastres Naturais (Projeto GIDES ou *Project for Strengthening National Strategy of Integrated Natural Disaster Risk Management* em inglês).

Este projeto, ainda em andamento, visa desenvolver ações de gerenciamento e intervenção em áreas propensas à ocorrência de desastres de movimentos de massa. A CPRM está a cargo de elaborar um dos manuais das diversas áreas do gerenciamento de desastres que visam padronizar nacionalmente uma forma de mapeamento e avaliação de áreas de perigo e risco a movimentos de massa (CPRM, 2018). Este material servirá para auxiliar as administrações públicas na preparação de estratégias de atuação frente a desastres e situações de emergência vivenciadas pela população.

Na elaboração dos manuais técnicos observam-se os preceitos da gestão integrada de desastres. Estes preceitos, em linhas gerais, consideram um ciclo por meio do qual os gestores responsáveis podem mitigar o impacto desses eventos separando-os em categorias de ações antes, durante e depois de sua ocorrência. Cada categoria encerra determinado número de fases, cada qual demandando um diferente conjunto de atividades, conforme descrito na **Tabela 1**.

Tabela 1 – Manuais que compõem o Projeto GIDES divididos pela fase dos eventos em que se inserem e o seu objetivo.

Antes do desastre	
Prevenção	Manual de Mapeamento de Perigo e Risco a Movimentos Gravitacionais de Massa.
Mitigação	Manual de Redução de Riscos de Desastres Aplicado ao Planejamento Urbano.
Preparação	Manual para Elaboração de Plano de Medidas Estruturais Contra Rupturas em Encostas.
Alerta	Manual Técnico para Concepção de Intervenções para Fluxo de Detritos.
Durante o desastre	
Alerta/Planos de Contingência	Manual Técnico para Elaboração, Transmissão e Uso de Alertas de Risco de Movimentos de Massa.
Depois do desastre	
Recuperação/ Desenvolvimento	Manual para Elaboração do Plano de Contingência Municipal.

1.4.1. MANUAL DE MAPEAMENTO DE PERIGO E RISCO A MOVIMENTOS GRAVITACIONAIS DE MASSA

O Manual de Mapeamento de Perigo e Risco a Movimentos Gravitacionais de Massa é o que está a cargo da CPRM. Ele foi disponibilizado ao público em março de 2018 em uma forma ainda não finalizada chamada de “versão de serviço - preliminar” e até a finalização deste trabalho se mantinha desta mesma forma.

Este manual é importante porque ainda há divergências a nível mundial e nacional quanto aos conceitos aplicados nos diversos tipos de mapeamentos, sejam eles de suscetibilidade, perigo ou risco que buscam nele ser sanadas, ao menos parcialmente, através da proposta de padronização. Há inclusive diferentes vertentes do significado desses distintos mapas, o que eles abordariam e inclusive qual seria a definição de cada um destes três termos (Brasil, 2007; Fell et al., 2008; Hervás e Bobrowsky, 2009). A seguir serão resumidos conceitos internacionalmente reconhecidos usando o exemplo original dos escorregamentos, porém estes termos podem ser aplicados facilmente para outros movimentos de massa e que neste trabalho serão utilizados para os fluxos de detritos.

A suscetibilidade a escorregamentos (*landslide susceptibility* em inglês) pode ser definida como a avaliação quantitativa ou qualitativa de classificação, volume (ou área) e distribuição espacial de escorregamentos existentes ou que potencialmente podem ocorrer em uma área, segundo o Comitê Técnico de Escorregamentos e Taludes Construídos das associações internacionais ISSMGE, IAEG e ISRM (JTC-1 – *Joint Technical Committee on Landslides and Engineered Slopes* em inglês), publicado em Fell et al. (2008). Eles dizem ainda que embora seja esperado que escorregamentos possam ocorrer mais frequentemente em áreas mais suscetíveis, na análise de suscetibilidades o período não é explicitamente levado em conta.

Segundo Fell et al. (2008) o perigo a escorregamentos (*landslide hazard* em inglês) é a condição segundo a qual há a possibilidade de ocorrência de uma consequência não desejada. A descrição de perigo a escorregamento pode incluir a localização, volume (ou área), classificação e velocidade de escorregamentos em potencial e qualquer material resultante avulso, e a probabilidade de ocorrência dentro de um dado período. Em outras palavras, o perigo pode ser explicado como uma espécie de suscetibilidade na qual inclui-se o fator temporal ou de recorrência. Por outro lado, o manual do Projeto GIDES usa a definição de perigo do Glossário da Defesa Civil Nacional (Ministério da Integração Nacional, 2009), na qual o perigo de escorregamento é "qualquer condição potencial ou real que pode vir a causar morte, ferimento ou dano à propriedade". Esta definição ainda propõe que o perigo é um dos elementos da identificação do risco. Desta forma, o conceito de perigo do manual do Projeto GIDES pode ser entendido como o de suscetibilidade do JTC-1.

O JTC-1 classifica o risco a escorregamentos (*landslide risk* em inglês) como a medida entre a probabilidade e a severidade, incluindo um efeito adverso a saúde, propriedade ou ambiente (Fell et al., 2008). O risco é frequentemente estimado pelo produto entre a probabilidade de um fenômeno de uma dada magnitude e as suas consequências.

Entretanto, uma interpretação mais geral do risco envolve uma comparação da probabilidade e das consequências de uma forma que não seja um produto. Ao contrário do ocorrido com o perigo, de forma menos detalhada, há certa convergência do manual do Projeto GIDES com a definição de Fell et al. (2008). Novamente o manual segue o Glossário da Defesa Civil Nacional (Ministério da

Integração Nacional, 2009) que diz que risco é uma “combinação da probabilidade de um evento e suas consequências negativas”.

O manual do Projeto GIDES objetiva definir padrões relacionados ao mapeamento e à avaliação de áreas de perigo e risco a movimentos gravitacionais de massa que tenham aplicabilidade em todo o território nacional, por meio da apresentação de um procedimento baseado em critérios topográficos e estatísticos.

1.4.2. O MÉTODO DE MAPEAMENTO DE PERIGO A FLUXOS DE DETRITOS DO PROJETO GIDES

O método proposto no manual do Projeto GIDES para elaboração de cartas de perigo a movimentos gravitacionais de massa objetiva identificar, por meio de critérios topográficos, quatro tipologias específicas de movimentos de massa tanto existentes como potenciais (queda de blocos, deslizamentos planares, deslizamentos rotacionais e fluxos de detritos). Além disso, procura também delimitar projeções para seu comportamento (área de geração e de atingimento) e qualificar sua gravidade, usando para isso indícios físicos do terreno.

No Brasil há estudos e coletas de dados em andamento em diferentes regiões com a realização de testes em áreas-piloto. Estes resultados são apresentados e discutidos em reuniões técnicas, com o objetivo de adaptar a técnica japonesa de mapeamento à realidade e aos dados brasileiros. A fundamentação para fluxos de detritos do manual se baseia resumidamente em correlações entre os métodos estatísticos japoneses e brasileiros, juntamente a levantamentos complementares de campo realizados em Nova Friburgo - RJ, Petrópolis - RJ e Blumenau - SC (CPRM, 2018). Embora o manual seja mais abrangente, a partir deste ponto será demonstrado o procedimento de produção do mapa de perigo apenas para os fluxos de detritos, que são objetos deste estudo.

Primeiramente, define-se a área de estudos baseada no tipo de movimento de massa abordado e os locais de provável deflagração e atingimento. Após esta decisão, é necessário reunir os dados de entradas para o trabalho que são mapas topográficos com curvas de nível em escala entre 1:1.000 e 1:10.000 ou um modelo digital de elevação (MDE), sem que o manual diga as especificações em termos de resolução espacial. Também é muito importante ter a rede de drenagem e o histórico mais completo possível de movimentos de massa do local.

O manual diz que é preciso verificar a necessidade de mapeamento através da análise inicial de três características básicas para que uma bacia seja considerada propensa a fluxos de detritos. A primeira delas é a área da bacia, que precisa ser igual ou superior a um hectare, seguida pela inclinação média do talvegue que deve ser igual ou superior a 10°. Por último, o vale precisa ser considerado confinado através de medidas comparativas onde o comprimento dele deve ser maior que a sua largura. Aparentemente esta avaliação deve ser feita a cada intervalo entre duas curvas de nível onde no exemplo da **Figura 2** a largura do vale “a” deve ser menor ou igual ao seu comprimento “b” para ser considerado confinado. Porém, independente de tudo isso, se a bacia tem histórico de eventos deste tipo já é apta ao estudo, mesmo não atendendo aos pré-requisitos anteriores (CPRM, 2018). Segundo o manual, estes dados se originaram da “análise de dados japoneses e experimentos em municípios brasileiros”. O único detalhamento presente no manual com relação a esta seleção das áreas-alvo é que a condição de confinamento foi extraída unicamente de dados japoneses.

O processo para a produção dos mapas proposto pelo manual técnico do Projeto GIDES (CPRM, 2018) consiste posteriormente em delimitar a bacia e destacar as drenagens ou linhas de fluxo, além dos pontos iniciais e de espraiamento. Estes pontos indicam respectivamente o local onde se inicia a condição de confinamento descrita acima (**Figura 2**) onde se iniciaria o fluxo de detritos (a montante) e onde ela terminaria e seria o começo da dispersão do material em forma de leque (a jusante). O texto ainda diz que as drenagens sem confinamento ou registro de fluxos de detritos devem ser desconsideradas do estudo.

Em seguida é necessário traçar, a partir do ponto inicial, linhas transversais ao longo do canal com espaçamento máximo de 50 metros até a linha no ponto de espraiamento e novamente a partir dele a jusante até atingir a declividade de 2°.

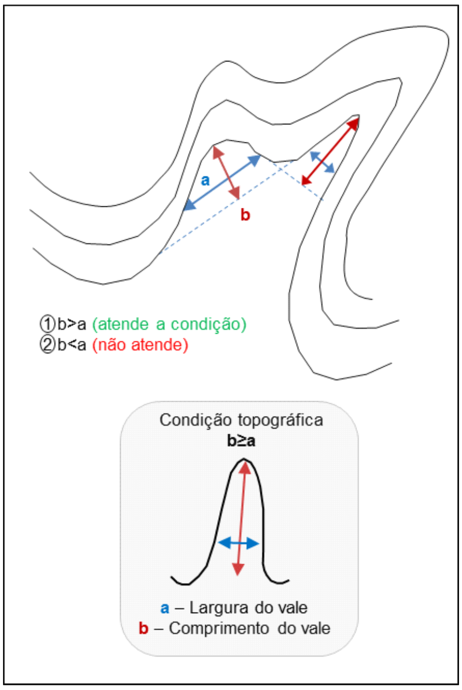

Figura 2 – Forma de cálculo da condição de confinamento dos vales (retirado de CPRM, 2018).

A área crítica é determinada até o ponto de espraiamento, sendo a zona com maior probabilidade à deflagração e atingimento dos fluxos de detritos, onde a energia está concentrada. Para sua determinação espacial é preciso marcar dois pontos elevados topograficamente 5 metros com relação ao nível do canal em cada uma das margens das linhas transversais. Estes pontos devem ser ligados para que surja a área crítica nos trechos confinados.

Para os trechos não confinados, ou seja, após o ponto de espraiamento, é necessário, ao invés do desnível de 5 metros, considerar uma extensão horizontal nas linhas transversais de 20 metros para cada uma das margens. Este procedimento deve ser feito até declividades de 7°. Novamente devem-se ligar estes pontos para criar a área crítica no trecho não confinado. A área crítica total é a junção destes dois polígonos recém-criados.

A área de dispersão é a região onde ocorre a deposição dos detritos e onde a energia se dispersa. Para delimitar este setor é necessário, assim como anteriormente, marcar dois pontos elevados topograficamente 5 metros com relação ao nível do canal em cada uma das margens das linhas transversais. Contudo, na área de dispersão há uma importante disseminação lateral do fluxo de detritos. Para contemplar este movimento o manual do Projeto GIDES diz que é necessário considerar um ângulo de dispersão fixo de 30°. Portanto, a partir do ponto de espraiamento devem-se criar pontos na primeira linha transversal seguinte com um ângulo de 30° distanciando-se do canal, como mostrado na **Figura 3**. A partir destes, criar outros pontos na linha posterior com o mesmo ângulo e seguir até a última transversal que, lembrando, deve estar até a declividade do terreno atingir 2°.

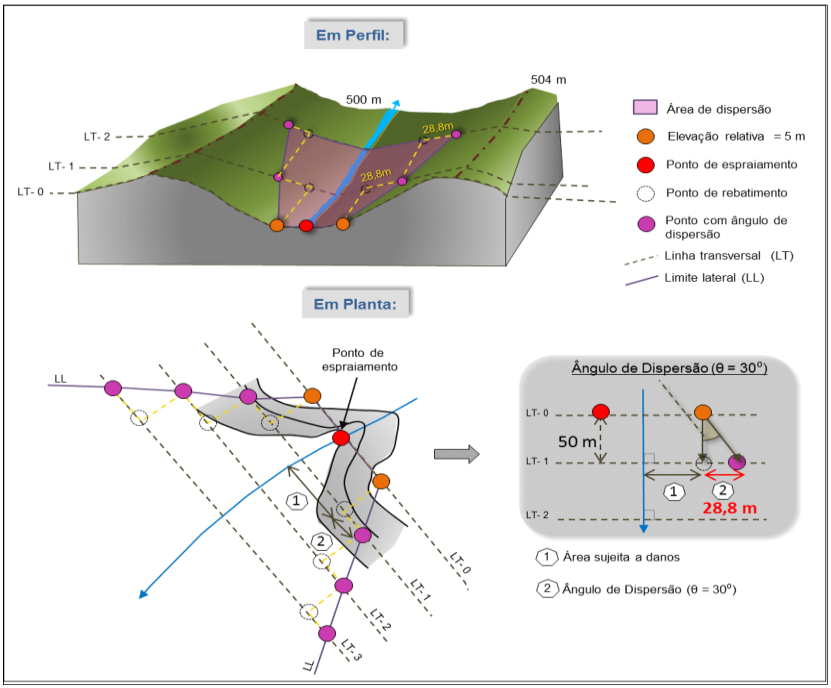

Figura 3 – Demonstração do posicionamento dos pontos criados a partir do ângulo de dispersão de 30° ou da elevação relativa ao canal de 5 metros para a delimitação da área de dispersão (retirado de CPRM, 2018).

Para finalizar a delimitação da área de dispersão é preciso escolher os pontos mais próximos ao canal em cada margem, ou seja, entre os criados a partir do ângulo de dispersão ou da elevação relativa de 5 metros (**Figura 4**). Estes pontos escolhidos de cada linha transversal devem ser ligados para concluir o polígono.

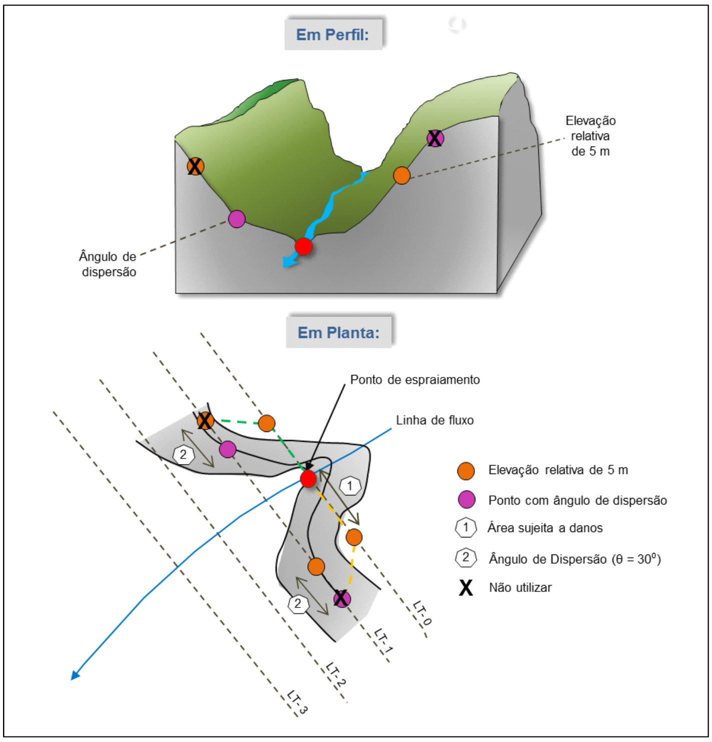

Figura 4 – Demonstração da escolha entre os pontos criados a partir do ângulo de dispersão de 30° ou da elevação relativa ao canal de 5 metros para a criação do polígono da área de dispersão (retirado de CPRM, 2018).

Estes dois polígonos criados a partir das etapas descritas perfazem as áreas crítica e de dispersão. Juntas elas formam o mapa de perigo a fluxos de detritos segundo CPRM (2018). A etapa seguinte é a de qualificação dos graus de perigo por meio de vistorias de campo para validar os critérios e as condições topográficas, além de avaliar os índices físicos de instabilidade do terreno.

Para o caso dos fluxos de detritos o manual cita que bacias com depósitos pretéritos deste tipo de movimento de massa já devem ser definidos como tendo "a área crítica como perigo muito alto (P4) e a área de dispersão como perigo alto (P3)". Em caso de ausência de tais depósitos, considera-se a correlação entre informações sobre a área da bacia, a inclinação do leito do canal e a espessura média do material depositado no canal (margens e fundo) através de tradagem. As tabelas de classificação e correlação foram retiradas de MLIT (1988). O presente trabalho limitou-se a testar e analisar até esta etapa do manual, ou seja, até a espacialização e classificação em graus de perigo das áreas de deflagração e/ou atingimento dos fluxos de detritos.

Porém o manual traz também possibilidade de se fazer uma carta de risco. Ela é feita após a classificação de vulnerabilidade em classes (de V1 a V4) e seu cruzamento com a carta de perigo em uma “matriz de correlação entre a vulnerabilidade das construções (V) e o grau de perigo do terreno (P)” (CPRM, 2018). O resultado é dado em classes de risco adaptadas de BRASIL (2007) entre R1 e R4.

A fundamentação teórica do manual do Projeto GIDES é relativamente simples e curta, e mostra que o material foi produzido através da mistura de técnicas internacionais e dos trabalhos de campo no Brasil que trouxe a prática japonesa para a realidade local. Segundo o manual (CPRM, 2018), estas adaptações mostraram que na maioria dos casos a deposição dos fluxos de detritos ocorre entre 2 e 5° de inclinação, por isso o mapeamento se limita inferiormente a declividades de 2°.

A área critica acaba quando a declividade atinge valores menores que 7° porque em observações de campo feitas pela CPRM constatou-se que a destruição se amplia com o aumento da declividade e consideravelmente após cerca dos 7°. Além disso, concluiu-se que quando o fluxo de detritos não está confinado em um canal a extensão lateral a ser adotada deve ser de 40 metros, ou seja, 20 metros em cada margem e que não há direção específica de deposição. O estudo dos casos em campo e a estatística trazida do Japão adotaram 60°, sendo 30° para cada margem. Outro dado adotado diretamente da prática e das estatísticas japonesas foi que a altura do fluxo a ser inferida de 5 metros (CPRM, 2018).

1.5. ÁREA DE ESTUDOS

A área de estudo deste trabalho localiza-se no litoral do Paraná, mais precisamente entre os municípios de Morretes e Paranaguá, na região noroeste da Serra da Prata (**Figura 5**). Paranaguá possui população estimada em 2016 de 151.829 pessoas e área de 826 km² (IBGE). Morretes possui população estimada em 2016 de 16.488 pessoas e área de 685 km² (IBGE). O local atingido pelos fluxos de detritos se chama Comunidade Floresta e era composto por 83 casas antes do desastre.

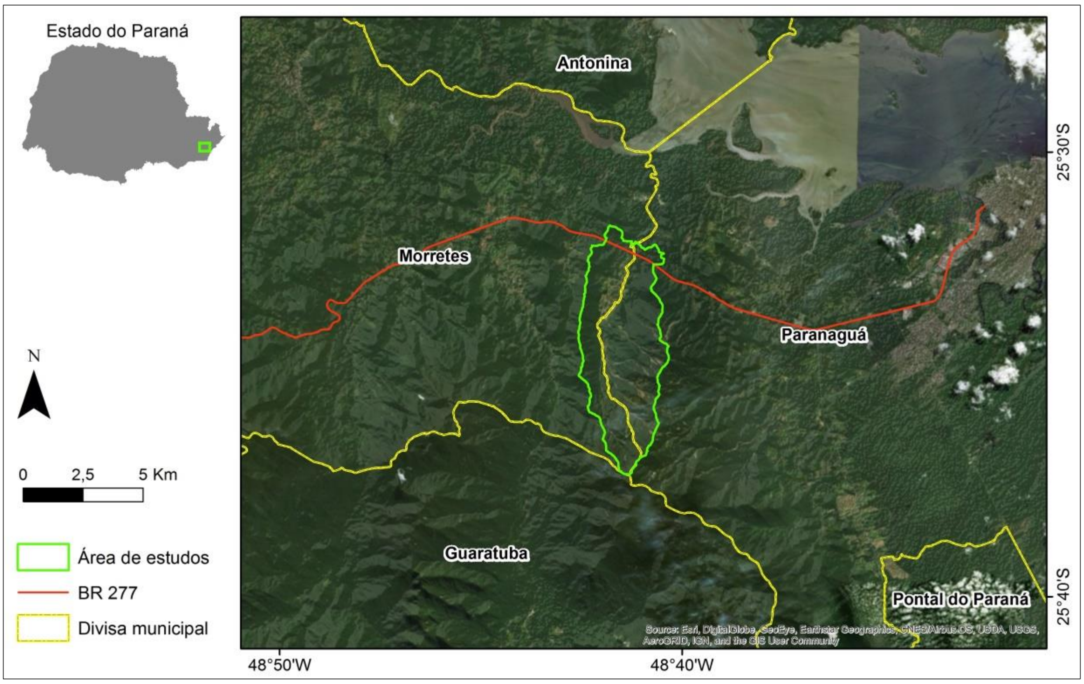

Figura 5 – Localização da área de estudos no estado do Paraná e em seu litoral. Datum horizontal: SIRGAS 2000.

Nos dias 11 e 12 de março de 2011 fortes chuvas causaram mais de 2.500 movimentos de massa de diversos tipos, sendo que os principais foram escorregamentos e fluxos de detritos (Geoplanejamento, 2011). Estes últimos tiveram mais relevância na Comunidade Floresta devido ao seu tamanho, destruição e por ter causado um óbito (**Figura 6**).

Considerando os registros encontrados no local, a bibliografia nacional consultada especificamente sobre a área (como Geoplanejamento, 2011; Picanço & Nunes, 2013; Picanço et al., 2016; Pinto et al., 2012, Silveira et al., 2013 e outros) e o relato dos moradores, conclui-se que o que ocorreram lá foram majoritariamente fluxos de detritos.

A Serra da Prata, na parte leste da bacia do rio Jacareí, foi um dos locais mais atingidos pelos fluxos de detritos em março de 2011. Ela é uma cadeia montanhosa praticamente N-S sendo parte integrante da Serra do Mar Paranaense com altitudes que chegam a mais de 1.400 metros (Mineropar, 2006-A). Segundo a classificação de Köppen-Geiger o clima varia desde tropical úmido a temperado úmido com verão quente a temperado (ITCG, 2008). Os principais solos da bacia são neossolos líticos nas áreas elevadas, cambissolos e argissolos a montante do rio Jacareí e gleissolos a jusante que juntos sustentam a vegetação densa da Mata Atlântica (Mineropar, 2006-A). Em campo verificou-se que os solos são majoritariamente argilosos.

Figura 6 – **(a)** Aspecto geral da Serra da Prata pouco após a ocorrência dos fluxos de detritos (imagem da MINEROPAR). **(b)** Áreas de deposição de matacões (à direita) e de sedimentos finos (à esquerda). **(c)** Canal com depósitos de fluxos de detritos. **(d)** Atingimento de casas por sedimentos finos e grandes troncos de árvores (as três fotografias são da Agência de Notícias do Paraná).

Sua geologia é predominantemente composta por uma suíte granítica foliada. Além disso, ocorrem faixas de xistos compostas por biotita-muscovita xisto com clorita, com ocorrências locais de quartzo xistos e quartzitos. Os sedimentos recentes estão representados por depósito de tálus e blocos e coluvios ns vertentes e nos sopés de montanha. Nas porções mais baixas, ocorrem aluviões de origem fluvial. Estes sedimentos podem mudar para mangues e depósitos marinhos a jusante (Mineropar, 2006-B).

Esta área foi escolhida para ser estudada pelo grande evento ocorrido recentemente. Além disso, as condições geológicas, geomorfológicas e geotécnicas complexas aumentam o desafio de se trabalhar ali.

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2. EVALUATIONS AND PROPOSALS FOR THE DEBRIS FLOWS HAZARD MAPPING METHOD OF THE GIDES PROJECT

Abstract

On March 11th and 12th, 2011, a large rainfall event caused floods and thousands of gravitational mass movements that caused deaths and material damages in the coast of Paraná. This work focuses on the large debris flows that have reached the Jacareí river basin and uses them to test the new hazard mapping method proposed by the GIDES Project. This project is a technology transfer partnership of natural disasters management and prevention between the governments of Brazil and Japan. Although simple and fast, the proposed method did not show results consistent with the reality when done in its original form, in addition to the fact that the basin in question would not meet the minimum morphometric requirements to be initially mapped. However, after adaptations to the studied case, major improvements could be noticed. For the debris flow transportation area it was concluded that the relation that produced maps closer to the event studied was the relation between the maximum height reached by the flow with the maximum channel slope for each channel section. No satisfactory morphometric relationship was found for the boulders deposition region. But, for the area of fine or less dense materials deposit, the most significant change was the incorporation of slopes from 0 to 2° in the mapping procedure. In the evaluation of basins to be mapped, the prerequisites of the GIDES Project method did not fit the studied case. Therefore, the method used by IPT/CPRM was employed with some suggestions and increments. This procedure was able to separate the basins prone to debris flows from the non-prone with perfect adjustment. After all the analysis, it was possible to find values and equations that could be used initially in the analysis of other basins with some similarity with the studied area to map the debris flow susceptibility, although a validation in other places is still needed. These different techniques adapted to the local reality can be used separately or together to create faster, simpler, cheaper and reliable maps using relatively easy to find input data.

Keywords

Debris flow, hazard mapping, Jacareí river, basin morphometry, GIDES Project.

2.1. INTRODUCTION

Debris flows are one of the most dangerous forms of mass movements. They are very rapid flows of detrital material that can carry huge boulders descending by gravity in deep channels and reach great mobility (Hungr et al. 2014). Much of the worldwide mass movement deaths are due to debris flows and their volcanic counterpart, the lahars (Jakob & Hungr, 2005).

Disasters related to debris flows occurrence that took place in Brazil in 2008-2011 produced thousands of deaths, millions of affected people and a huge economic loss. These were a real mark for the Brazilian Government to regulate and administrate better national urban planning, civil defense and disasters' management (CPRM, 2013).

Among these governmental actions was the creation of the Project for Strengthening National Strategy of Integrated Natural Disaster Risk Management or GIDES Project. It is part of a partnership for technology transference between Brazilian and Japanese governments. One of its main objectives is “strengthen risk assessment capacity in mass-movement disasters including hazard identification, vulnerability analysis, and mapping” (GIDES, 2018). It has also reached, through the production of six manuals, the definition of hazard and risk mapping and evaluation standards on gravitational mass movements to be applied nationwide (CPRM, 2013).

Debris flows hazard mapping is on the GIDES Project as the “Hazard and Risk Mapping on Gravitational Mass Movements” manual. It was produced by the Geological Survey of Brazil (CPRM). The proposed empiric method uses topographic and basin morphometry measurements for the calculation of mass movements critical and dispersion areas (explained below). Its technique is in accordance to international studies trends (i. e. Wilford et al., 2004, Cascini, 2008, Vahidnia et al., 2010 and Hungr et al., 2014).

GIDES Project is carried by the Brazilian Government and is a promising mapping procedure that might be used widely as a standard. Considering its future importance, this paper aims to test the suggested method using the debris flows of March 2011 at the Western Serra da Prata mountain range as an assumption to discuss its effectiveness.

It is a novel procedure and needs to be tested in different locations, as made on this study. This work uses morphometric parameters to propose improvements for what is proposed in the GIDES Project's manual in order to turn it in a more trustful national procedure. For caparison, we also apply morphometric methods such as the IPT/CPRM, widely used in Brazil.

2.2. MATERIAL AND METHODS

The GIDES method to map the hazard of debris flows is based on correlations between Japanese and Brazilian empiric statistical methods, corroborated with field surveys conducted in the Brazilian cities of Nova Friburgo, Petrópolis and Blumenau. According to the current version of the GIDES Project manual (CPRM, 2018), the necessary input data is simple: the contour lines of the study zone from a topographic map on a scale between 1:1,000 and 1:10,000 or a DEM (Digital Elevation Model) without stating specific spatial resolution, its extracted drainage and the local mass movement historic record. For this research we used an ALOS Palsar DEM with spatial resolution of 12.5 m generated before the event at Serra da Prata.

First it is required to verify if the studied region would be prone to debris flows and, consequently, needs to be mapped. According to the GIDES manual, the basin area should be greater than 1 ha, the mean slope of the thalweg should be at least or more than 10° and has to comply to a rule of valley's confinement (their length must be greater than its width).

Once attending these requirements, the drainages, flow lines, and starting and dispersion points should be highlighted. The starting point is where the confinement starts at the beginning of the channel and the dispersion point is a transition spot where valley confinement ends. After this delimitation, it is necessary to make transverse lines along the flow line at every 50 meters or less towards slopes of 2°.

The critical area is the region with the greatest probability for debris flow triggering and material reaching. The critical area on confined tracks is determined at the points where each of the transverse lines is topographically 5 meters higher than the channel's bottom within the same line, repeating this procedure toward the dispersion point (**Figure 7**). These values were adopted directly from the Japanese methodology whose statistics conclude the flow heights are 5 meters on the critical zone, where the drainage is confined (CPRM, 2018).

The critical area on unconfined tracks is defined by horizontal distances of 20 meters for each traced perpendicular line limited to slopes above or equal to 7°.

This value was adopted because field observations by CPRM (2018) showed that destruction increases with a slope angle increase and considerably above 7°. In addition, CPRM's field data showed the studied debris flows records have a major destruction for horizontal amplitudes above 20 meters measured at each margin, without a specific deposition direction.

From the dispersion point is the area where the flow would disperse from the channel on the same altimetric difference of 5 meters or a horizontal dispersion angle of 30° for each side on the perpendicular lines causing material deposition and the spreading of the flows' energy. This zone is called dispersion area and it is delimited choosing the points closer to the channel between the altimetric difference or the dispersion angle (**Figure 7**).

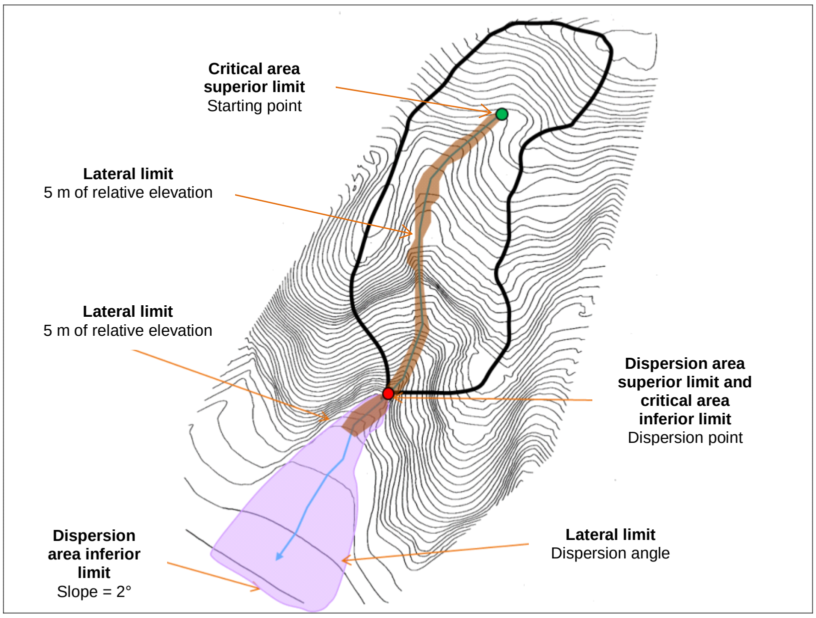

Figure 7 – Final debris flow hazard map using the GIDES method. The brownish zone is the critical area and the purple zone is the dispersion area. Image modified from CPRM, 2018.

These delimitation processes are made towards an inferior slope angle limit of 2°, which the necessary energy for the flows to be considered dangerous or destructive would be ended. According to Brazilian and Japanese records, most cases debris flows deposition occurs in slopes between 2 and 5°. All these procedures are summarized in the flowchart of **Figure 8** and detailed in CPRM (2018).

The GIDES manual uses the definition of hazard from the National Civil Defense Glossary (Ministry of National Integration, 2009), in which the landslide hazard is "any potential or actual condition that could lead to death, injury or property damage". This definition further proposes that hazard is one of the elements of the risk identification. In this way, the concept of hazard in the GIDES Project manual can be understood as the JTC-1 susceptibility (Fell et al., 2008).

Although the manual cites just debris flows, it probably includes also debris floods (according to Hungr et al., 2014) or hyperconcentrated flows (according to Pierson, 2005). It defines debris flows in a simple form as a fast fluid mass of high viscosity composed mainly by soil, rock, vegetation, anthropic debris and water. This features can characterizes debris flows as well as other mass movements of the flow type. There is no specific behavior or sediments percentage to be more restrictive.

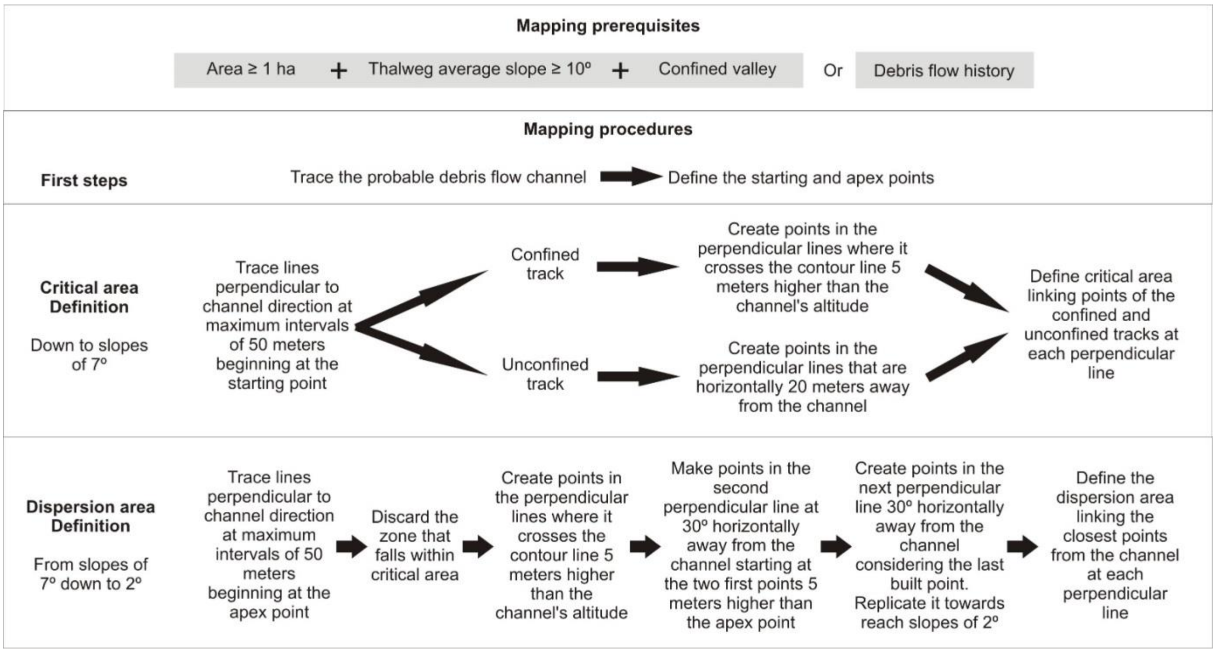

Figure 8 – Flow chart summarizing the GIDES Project methodology for debris flow susceptibility mapping.

It is important to notice that the results produced here were made only with information from the GIDES Project manual. The goal was to map the same way as any user who reads the manual.

The other tested method also uses basin morphometry. A susceptibility mapping procedure to be carried out at municipalities in Brazil in a 1:25.000-1:50.000 scale was consolidated in 2013 from a partnership between the Institute for Technological Research of the São Paulo State (IPT-SP) and the Geological Survey of Brazil (CPRM) called here as IPT/CPRM method. The intention of this method is to be applied to areas with little terrain information and aims to be easily understandable by lay people. It focuses on distinguishing basins prone to debris flows, flash floods and clear water flows using morphometric parameters.

The IPT/CPRM technique is described by Corsi et al. (2015). To be prone to debris flows and flash floods the basin should be previously mapped and considered highly susceptible to landslides, the watershed area should be smaller than 10 km², geomorphologically classified as mountain ranges or high hills, a Melton index ($M = (H_{max}-H_{min})/\sqrt{A}$) higher than 0.3 and also as prerequisite an altimetric gradient higher than 500 meters. The watershed with altimetric gradient between 499 and 300 m and/or a Melton index lower than 0.3 is considered prone only to flash floods.

The preceding authors also consider the Melton index easy to use and efficient to discriminate debris flow and flash flood basins. They adopted the same limits (0.3) of Jackson et al. (1987) used in Canada. But it is not clear why Corsi et al. (2015) suggest using the altimetric gradients of 300 and 500 meters to differ the predominant event in each basin. The authors state that every debris flow basin can also generate flash floods, but not the other way around.

Besides the morphometric indexes used on the IPT/CPRM method, it was tested also parameters studied by Wilford et al. (2004), Chen & Yu (2011) and Rogelis & Werner (2014) detailed in **Table 2**.

Table 2 – Morphometric parameters tested at the studied area.

Parameter	Objective	Applied area	Authors
Total length of channels	Energy indicator (describes event type)	Whole drainage basin	Wilford et al. (2004)
Drainage density			
Relief ratio			
Mean slope	Debris flows initiation conditions	Source area	Wilford et al. (2004), Chen & Yu (2011)
Effective basin area (A15)	Identify topographic features of debris flows	Whole drainage basin	
Relief ratio			
Elevation-relief ratio			
form factor or shape factor			
Sediment transport capacity index (LSRUSLE)			
Stream power index (SPI)			
Topographic wetness index (TWI)			
Runout distance on the fan			
Terrain characterization index			
Flow direction and accumulation			
Watershed perimeter	Energy indicator (describes event type)	Whole drainage basin	Rogelis & Werner (2014)
Watershed width			
Mainstream length			
Length-to-width ratio			
Hypsometric integral			
Watershed mean slope	Energy indicator		
Mainstream slope			
Drainage density	Indicates flood or flow potential		
Form factor or shape factor	Energy indicator (indicates flood or flow potential)		
Elongation ratio	Energy and erosion indicator (flood or flow potential)		

2.3. STUDY AREA

The studied area is in a mountainous part of the Paraná State coast, Southern Brazil (**Figure 9a**). It was struck by hundreds of landslides that fed debris flows and debris floods on seven rivers or streams probably almost at the same time in the hydrological disaster on March 11th and 12th, 2011. There is a community on the Jacareí river region with 83 houses at 2011 of which 17 were partially destroyed and 11 were totally destroyed (Geoplanejamento, 2011).

On a regional view, several floods, landslides, and debris flows caused two deaths and 200 injured in the municipality of Antonina, one death and 21 injured in Morretes and left two thousand dislodged people. In addition, the material losses of these two cities, together with Guaratuba and Paranaguá, amounted to more than 63 million US dollars due to the destruction of crops, public and private equipment, and other losses. (State Coordination of Protection and Civil Defense of the Paraná State, 2011). Antonina and Morretes declared a state of public calamity and Paranaguá declared emergency situation. The event is still notable even seven years after the event because the ruins of many buildings are still intact. Otherwise, the vegetation has already grown and replaced the empty spaces left by the passage of many landslides and flows.

This statewide disaster was caused by continuous and intense rains concentrated in just a few days. The annual rain average is 2,284 mm and March has an average of 271 mm (data from INMET) which sustains very dense vegetation in the area. On 2011 it was registered volumes of 382 mm on four days before the event (data from SIMEPAR). According to Picanço & Nunes (2013), at the beginning of March 2011 more than 600 mm of rain was recorded in some gauges in the affected region. Additionally, just before the main debris flows deflagration time, 49 mm of rain was registered in just one hour at the closest gauge on the afternoon of March 11th of 2011 (rain gauge of the INMET at Morretes, data from SIMEPAR).

The **Figure 9b** shows the distribution of the events in the studied region and will be the base to compare the produced hazard maps. It was created based on the photointerpretation of Worldview1 and Rapideye images (from June/2011 with spatial resolution of 0.5 meter and from May and June/2011 with spatial resolution of 5 meters, respectively). This map was modified from the debris flows and landslides inventory made by Geoplanejamento (2011). Their interpretation was adapted and divided to the reality seen on the field to better represent the studied mapping methods.

The highest altitudes (more than 1,400 m above sea level, which is also the altimetric difference of the basin) of the Jacareí river basin are mainly comprised of granitic rocks. They are lightly deformed and locally gneissic. Serra da Prata is supported by the foliated granitoids of the Paranaguá batholith. Locally, bands of schist from the Rio das Cobras formation occur. All these rocks are cut by diabase dikes, which condition the watershed direction (Cury, 2009; Geoplanejamento, 2011). These rocks have produced a soil with large amounts of clay and silt and high thickness variability, ranging from just less than a meter to more than 20 meters, as seen at the field.

Colluvium-alluvium deposits are related to the Alexandra Formation sediments (Miocene) and recent debris flows and mud flows deposits (Cury, 2009 and Angulo, 2004). Geoplanejamento (2011) describes alluvium located on the lowest flatted areas filling the basin’s bottom with sand. A considerable part of it is surrounded by colluvium deposits that also go uphill following creeks on the southeastern watersheds. Talus deposits can be found at higher altitudes of the Jacareí river and at some other minor drainages on the center-north zone at lower altitudes.

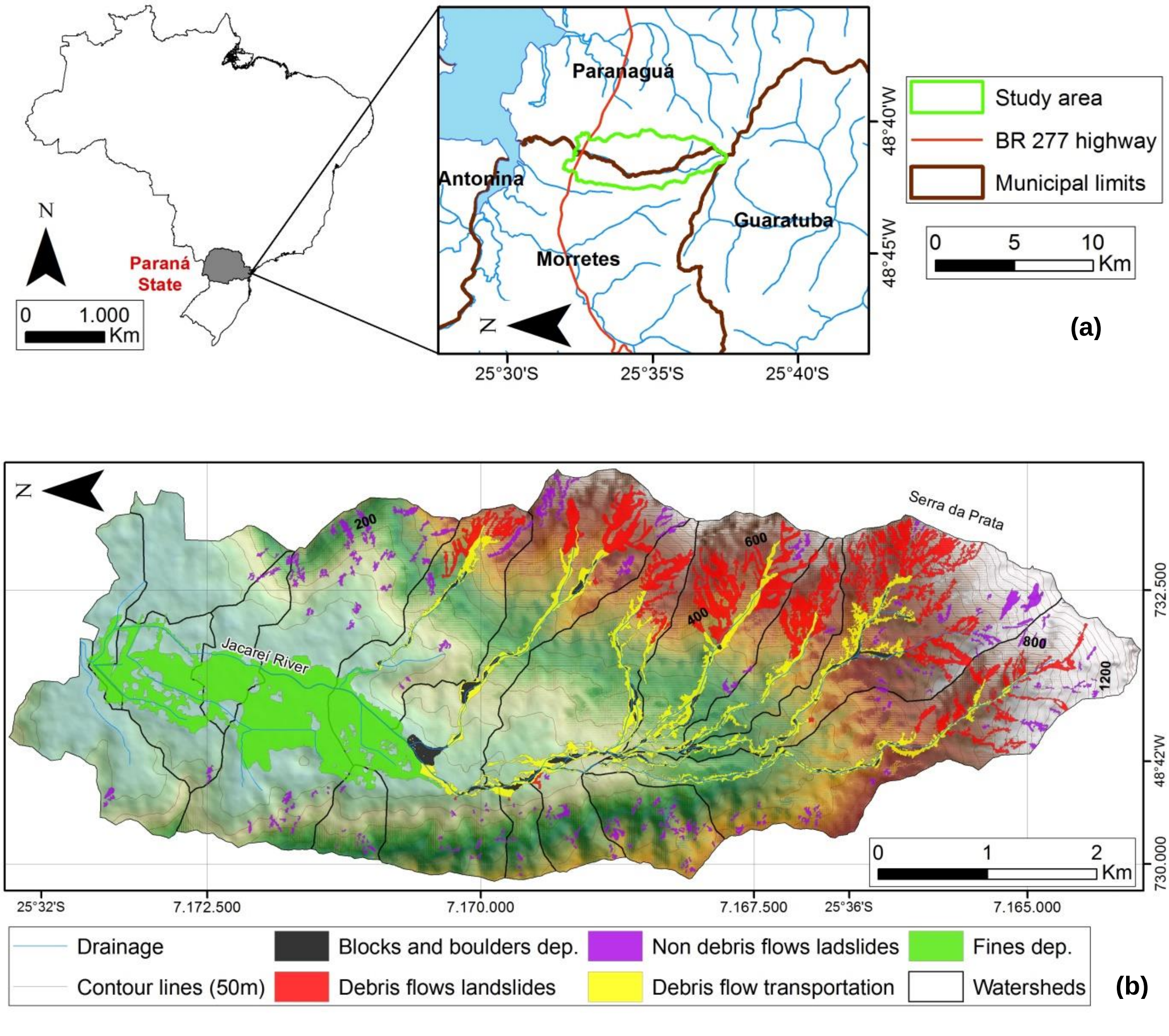

Figure 9 – **(a)** Serra da Prata and the Jacareí river basin localization map inside Brazil and Paraná State. **(b)** The lowest map shows the 2011 event inventory divided into five distinct compartments based partly on Geoplanejamento, 2011. Horizontal datum SIRGAS2000, UTM zone 22S.

For mapping purposes we believe that the dispersion or deposition zone needs to be divided in two. It was parted from images of the event time and observations on the field. One zone is composed of coarser sediments (as blocks and boulders) and further on the one with finer or less dense materials (as seen at **Figure 9b**). It is important to differentiate these two zones because they have different characteristics and, therefore, diverse destructive forces. The fine material dispersion zone in the studied area is not only composed of finer rocky material (finer than blocks as pebbles and sand) but also presents great part of its volume in form of vegetation, such as large branches and trunks. The mass movement, due to its high speed and energy, is able to transport large vegetation. The destructive power of this flow is very high as confirmed by many destructed building on that area. It may be called hyperconcentrated flow and sometimes debris flood depending on the region of the basin or the moment of the event (following the Pierson, 2005 classification).

Because of these characteristics, its freshness and the amounts of local studies, this area is suitable to test and propose improvements to the GIDES Project mapping method.

2.4. RESULTS

At first sight, the proposed GIDES Project method is simple, fast and effective when applied. But, as stated above, it initially involves a restricted confined valley requirement to set up a basin to be prone or not to debris flows. It says that for a watershed to be considered prone to debris flows, and therefore mappable, the target channel must be in a confined condition. By the manual, it means to have the drainage length between two topographic contour lines longer than its perpendicular line, also between the same contour lines. Without defining the confined track it is impossible by the GIDES manual to express the starting and dispersion points. The dispersion point is important because it marks the transition between the critical and dispersion areas, or transportation and deposition zones, where the flow is no longer confined. The Jacarei river watersheds are almost entirely not confined by these criteria while many had debris flows on 2011. Therefore, when using the GIDES methodology strictly as specified on the manual it was impossible to produce a hazard map because of its confined valley restriction.

Some adaptations were made on the valley's confinement rule and, consequently, on the dispersion and starting points placement to make a map (**Figure 10**). They were not considered to produce the map. Instead of using them, the map production adopted the manual's slope angle limits to delimitate the critical and dispersion areas.

The critical area is where the material is transported, but also where some blocks and boulders accumulates. As the manual states, it was delimited based on a 5 meters vertical buffer towards an inferior slope limit of 7°. The differences from the original form are that it started where the 1^{st} order channel begins and was made the vertical buffer all the way to the slope angle limit of 7°. The 20 meters of horizontal buffer after the dispersion point was not used, once it could not be placed. Therefore, we used the slopes inferior and superior limits of 7° and 2°, respectively to outline what would be the dispersion area based on zones where this slope range started to be more abundant along drainages and their surroundings.

The manual instructs to make this procedure using lines perpendicular to the drainage with a maximum interval of 50 meters between them and then to calculate the 5 meters topographic difference on each side. But in order to obtain a more detailed result, the DEM spatial resolution was used as the interval to trace the perpendicular lines, that is, for every 12.5 meters. The vertical buffer was made trying to obtain a more detailed map to highlight possible problems the method could have and to decrease errors that could appear because of the DEM relatively low spatial resolution for this use.

The map based on the GIDES procedure (CPRM, 2018) has also demonstrated to be relatively simple and fast to be produced after surpassed the difficulties on adjusting the originally proposed methodology to an area with non-confined drainages. But the result (**Figure 10**) does not appears to be very efficient to the real case studied. Comparing the predicted areas to the map of the real debris flows transportation and initiation zones at the channels occurred in 2011 (based on **Figure 9b**), 88% of the area affected by the event was classified as susceptible. This could be considered very good, however a large area of false positive and negative was also generated.

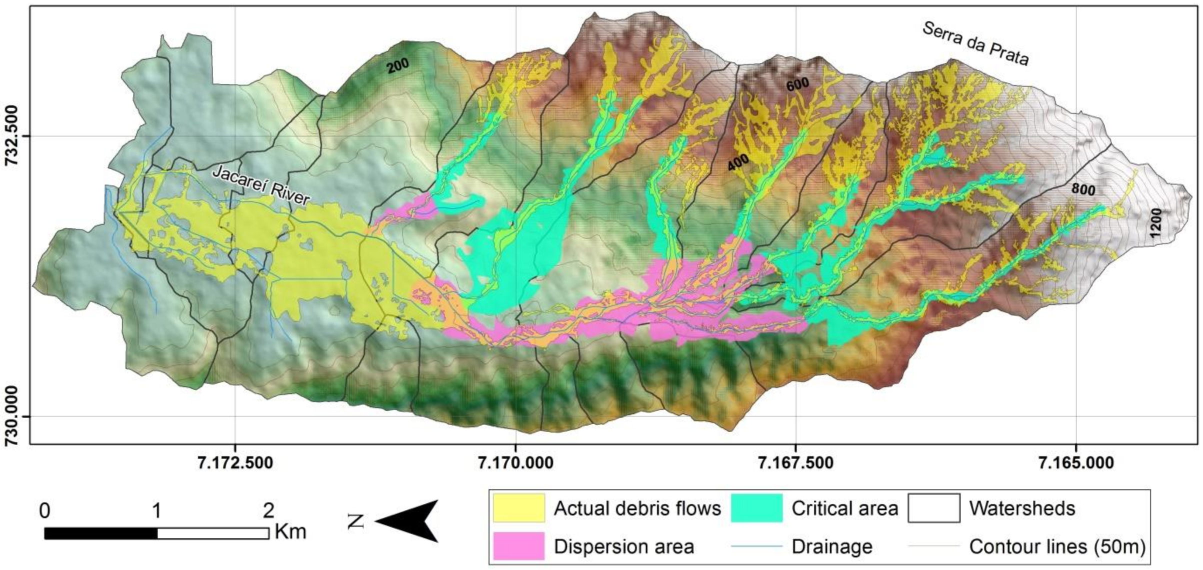

Figure 10 – Debris flow susceptibility map made based on the GIDES method with minor modifications on the confinement valley restriction and the starting and dispersion points placement. The resulting map is compared with the actual debris flows of the 2011 event. Horizontal datum SIRGAS2000, UTM zone 22S.

Considering the critical area of the map (**Figure 10**), for each 1 m² of true positive area there are 3.7 m² and 0.4 m² of false positive and negative, respectively. For the dispersion area, for each 1 m² of true positive there are 2.2 m² and 3.0 m² respectively of false positive and negative. It means that the method is very assertive for the critical area, but it is also super estimated and considers many safe areas as susceptible to debris flows.

Additionally, the dispersion area has even more problems because 93% of the real dispersion area was not considered on the map and has high values of false positives and negatives which means that these mapped areas were on the wrong place. Many safe areas were projected as hazardous to debris flows and other many zones actually affected by the 2011 event were considered safe. Almost all of the false negative areas have slopes equal or below 2°. In contrast the GIDES manual disregards this area as hazardous.

These performance values were created from comparisons between the produced maps from the modified GIDES technique and the mapped areas where debris flows from March 2011 were initiated, transported and deposited (not considering the landslides). **Figure 11** shows this data as “Mod.”, where “Mod. – Critical A” is the analysis for the critical area, “Mod. – Dispersion A” is for the dispersion area and “Mod. – Total A” is for the whole mapped zone that includes the critical and dispersion area analysis. That graph was made comparing the false positive, false negative and true positive with the area of the real event for the analyzed part.

Because of all those issues described above, it was necessary to produce maps with the GIDES methodology attempting not to stray from its basic principles. All the mapping suggestions below can be made as in the original GIDES method, where only zones of probable occurrence of debris flows are mapped, or as we called in a “binary” form (yes or no, 100% or 0%), or where different hazard classes are delimited, such as low, medium and high. This division into classes is used on several maps (i.e. Yin et al., 2017) because it brings to the result besides a way to further detail debris flows occurrence possibility.

2.4.1. CRITICAL AREA

Altimetric difference is the main determining factor of debris flow reach in the critical area according to the GIDES manual. This height should be set at 5 meters from the channel base level, regardless of location or material volume, for example. This value was based on flows studies in Japan, where most times it occurred in areas with a lower height than 5 meters (CPRM, 2018).

In order to verify it, other debris flows’ characteristics in the studied region were observed and several drainage morphometric features were extracted, analyzed and compared (**Table 2**). So, straight lines perpendicular to the drainage were spaced 10 meters between them and numerous properties of these segments were investigated, along with these same drainage sectors and their intersection with the areas affected by the flows at the actual studied events.

The analysis of the perpendicular lines shows that 67% of the debris flows heights reached 5 meters from the channel and that another 26% reached from 5.1 to 10 meters. That is, almost everything while the mean is 4.5 meters (**Figure 12**). However, understanding that the method could be more accurate looking for affinities between the several simple channel morphometric characteristics and the flow height (as basic characteristics of the original manual from CPRM, 2018), it was possible to observe several relations or data concentrations between those different drainage parameters and its surroundings in order to find the best to produce a more accurate map for the critical area.

The best data relationships were found associated with channel sections slopes. The slopes of these sections bring interesting data concentrations along with the reached maximum height debris flow. Thus, the relationship found is between the maximum slope of the perpendicular lines, presumed as that at the channels banks, and the flow reached maximum height for the thousands of lines analyzed (**Figure 12**). Their data have a good correlation ($R^2 = 0.7035$). It came from crossing morphometric data of 3,743 lines and the maximum reached height by the actual debris flow.

The measure of the slope angle considers the bottom of the channel before the event as the lowest point. These values are the highest of the two river banks because it considers the most critical scenario for both banks. It was obtained outlining lines perpendicular to the channel with 70 meters length and computing their maximum slope angle. The length came from the mean plus one standard deviation of the actual studied debris flows' horizontal extent. Moreover, the DEM was used to delimitate the vertical range or height of the actual debris flows from the inventory (**Figure 9**) on the perpendicular lines.

Bringing this result to the map production, it can be said that from the measure of the maximum slope angle of a channel section it could be possible to infer the height that the debris flow could reach using the same procedure of the perpendicular to the channel lines construction proposed by the GIDES manual.

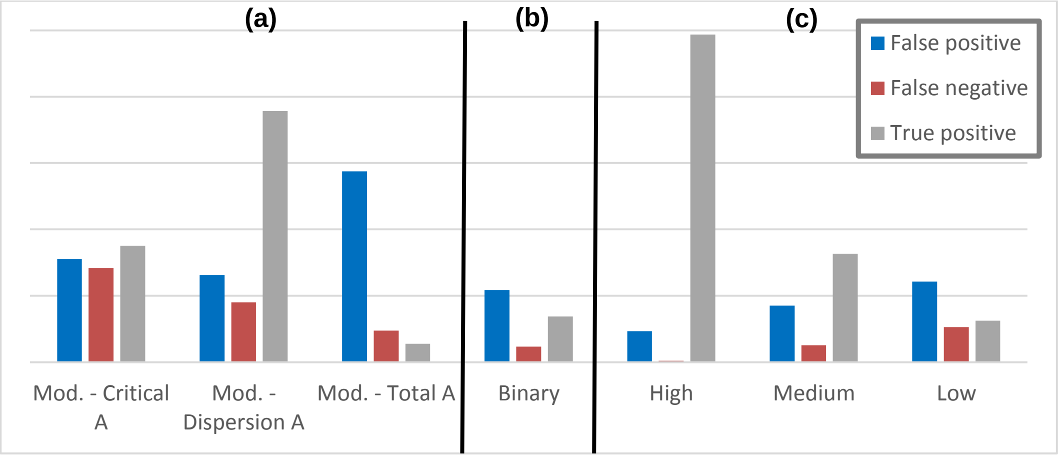

Figure 11 – **(a)** Analysis for the critical, dispersion and total areas of the slightly-modified method from the original GIDES method, **(b)** the binary form (prone or not) using the equation (1) for the critical area and **(c)** the three classes' model also for the critical area. It is shown on a non-dimensional unity to compare the form (or class) maps efficiency based on how low the value is, which means that the proportion of lower false positive and negative and higher true positive bars are more accurate.

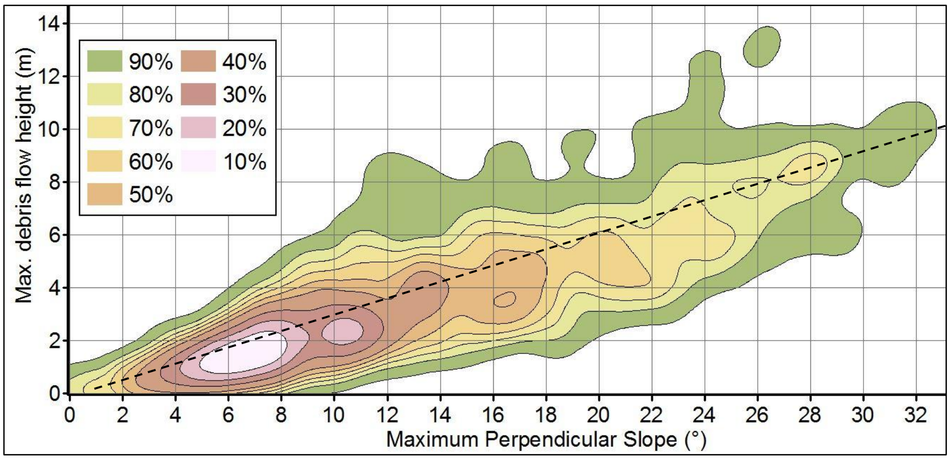

Figure 12 – Diagram of point density of maximum debris flow height x maximum perpendicular slope. The best matching morphometric attributes showing a trend and relation among these two parameters. From this diagram, it is possible to predict the maximum debris flow height based on the maximum perpendicular slope for each channel section. The dashed line represents the trend line.

There are at least two forms to use this relation of the **Figure 12** to produce hazard maps. The first one is choosing average measures in a test map in order to create three debris flows hazard classes in the sections considered as being in critical areas. The second is using the equation of the trend line from the graph.

In the first form, it was used for the low, middle and high classes, data concentrations values as 90%, 60%, and 30% were used, respectively (from **Figure 12**). These values generate fast maps with low values of false negative and false positive and high values of true positives. Results demonstrate that the map production with fixed values for high, medium and low classes have true positive as 29%, 55%, and 76%, respectively for data concentrations of 30%, 60% and 90% (**Figure 13b**). These numbers are very close of the expected ones compared to the occurred event; mainly for high and medium classes (true positive values should be as close as possible to the data concentration values).

Comparing their false negative percentages to their own total area for the different classes, they have the same proportion of 44-45%. But it is not suitable to apply equally to the false positive because the classes were made summing the higher susceptibility classes area. In other hand, it is possible to do it related to the real debris flow area where the values decrease for the false positive and increase to the false negative from high to low. The ideal, perfect map should have those values as low as possible. As classes go from high to low there is an efficiency increase as true positive increases much more than false ones, proportionally (in **Figure 11** as High, Medium and Low).

The second form to produce maps from the proposed relation of the **Figure 12** is to use the trend line of the equation (**1**) from the graph to scale the predicted debris flow at each drainage stage in critical areas:

$$H_{DF} = 0.3125S_{perp} – 0.2647 \quad \mathbf{(1)}$$

where H_{DF} is the maximum height reached by the debris flow relative to the channel bottom and S_{perp} is the maximum perpendicular slope of the channel and its surroundings (considering the two river banks). These values generated a binary map showing the locations of probable occurrence based on the event of March 2011. This was done using the equation values designating each meter higher than the drainage base level and its corresponding value in the slope that is shown in the same **Figure 12**. This is a more detailed product because it shows through a strong relationship between an important element for the GIDES method (maximum flow reach height) and a simple channel surroundings feature that can be easily extracted from a DEM (maximum perpendicular slope) (**Figure 13a**). The chosen maximum height reached by the debris flow interval of one meter could be different based on the available time for the map production, the desired detail level and DEM resolution.

Its resulting map analysis shows a true positive of 77% on the areas that debris flows occurred with relatively low false positive and negative indexes compared to previous maps based on the GIDES manual. These detailed values are in **Figure 11** as Binary and can be compared with the other results for the critical areas.

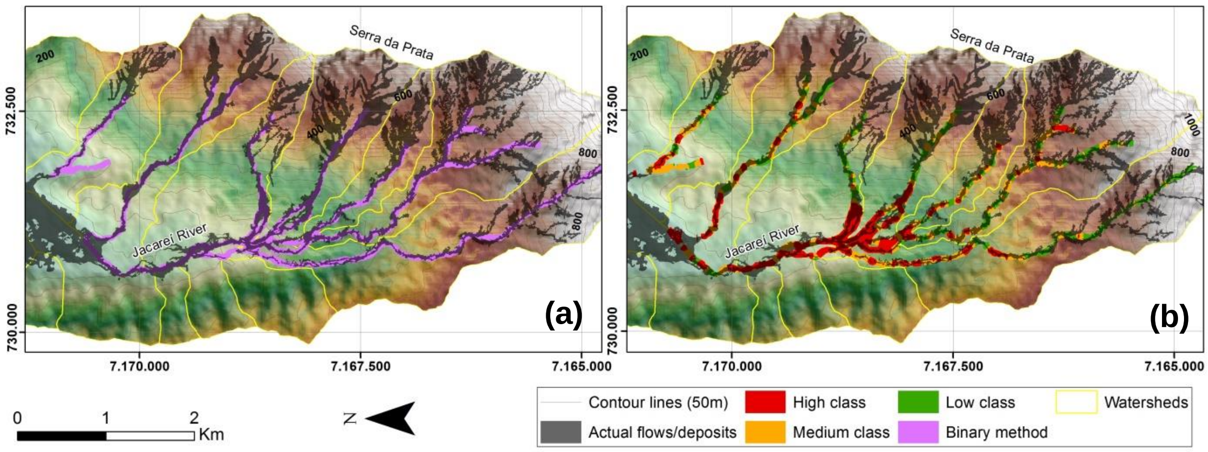

Figure 13 – Hazard maps showing the predicted reaching areas made from the proposed procedures for the critical area. **(a)** Map using the binary method. **(b)** Map with the different hazard classes. The resulting maps are compared with the actual debris flows of the 2011 event. Horizontal datum SIRGAS2000, UTM zone 22S.

It is important to note that on all these GIDES based maps, the hazardous area was limited horizontally by 35 meters on each side of the channel since some zones near the drainages appeared to be lower than the drainage itself, which is obviously unrealistic. This value originates from the upper limit of the areas actually reached by the debris flows studied corresponding to its mean plus a standard deviation.

Moreover, as the DEM spatial resolution used in all maps above is 12.5 meters, it was necessary to use a value correction. This adjustment consisted of removing these debris flows hazard areas pointed out as lower than the channel. The number that best corresponded to the reality was the removal of perpendicular to the channels areas shown as up to 3 meters below it using a vertical buffer procedure.

2.4.2. DISPERSION AREA

In the Jacareí river basin, it is possible to distinguish at least two sedimentation areas. As noted on the field work, the first occurs in sites not so steep and where the channels are less confined, either on the slope or reaching the valley bottom, in the dispersion zone. In these areas, mainly blocks and boulders are deposited in great quantity, forming true fans while finer sediments and much of the vegetation kept flowing forward.

Analysis of the March 2011 events summarized that blocks and boulders dispersion areas present deposition in terrain slopes between 0 and 25°, where more than 90% is concentrated between 3 and 16°, more precisely 54% between 4° and 10° (**Figure 14a**). This may show the deposition sites that could be considered as a possible mapping pattern on probable terrain slope conditions (as the main component considered in the GIDES method). But, of course, it still must be more widely tested and compared with other semi-confined or non-confined basins with similar characteristics (as many at Serra do Mar range).

However, this pattern of low specific slope concentration for coarse debris flow material deposition shows that in many sites with slopes of less than 16° deposition may occur. This fact does not exclude the flow transportation continuation on the channel or after (probably with smaller particles, but still very destructive). Proportions between slope classes of areas with debris flow transportation and with deposition are very similar, with discrete concentrations at smaller slopes. Therefore, it is worth remembering that the areas considered here as block and boulders deposition are also debris flows transportation sites. It also can be at least regions with occurrence of hyperconcentrated flows/debris flood on lower altitudes that deposited their remaining finer sediments (sand, pebbles, gravel, and vegetation) in the area considered here as fine material.

Considering the current GIDES method's binary form, it can be drawn in places where the slope is between 3 and 13 degrees, summing up 81% of the collected data. However, using different reliability classes we can classify as high values between 3 and 6 degrees, medium between 3 and 10 and low between 3 and 16 (30%, 65%, and 90% cumulative percentage, respectively), still considering the reasonable distance to the drainage of 35 meters.

The way these last maps were classified is very interesting because it would be able to represent even debris flows with different intensities in the same area. Areas classified as high hazard class have more chance to be affected even if the event was smaller, while low class does not. In addition, this data has to be tested in other areas in order to reduce false negatives and false positives more than true positives, generating a good relation between mapped area as susceptible and true positives in cases of occurred events to a given level of assurance.

We tried to generate maps with the suggested values above, though it is not as simple as it appears to be. Morphometric analyses were made, as the one made to outline the critical areas, and showed that there is no direct and simple relation between blocks and boulders deposition areas and slope as the previous case. It was also tested correlating these areas with drainage distance or angle (as the original GIDES method), but no direct relation was found and, therefore, no consistent maps could be created.

By the GIDES manual, areas with slopes between 0 and 2°should not be considered in any way for the mapping because these situations would not resume enough energy to cause damage. However, this study shows that about 57% of the flooded area and subsequent deposition of fine sediments (sands, pebbles, and large tree trunks) occurred between 0 and 2° of slope. The size and quantity of sediment deposited in the zone clearly show that these regions should not be forgotten. Proving this argument, several constructions were seriously damaged or destructed there.

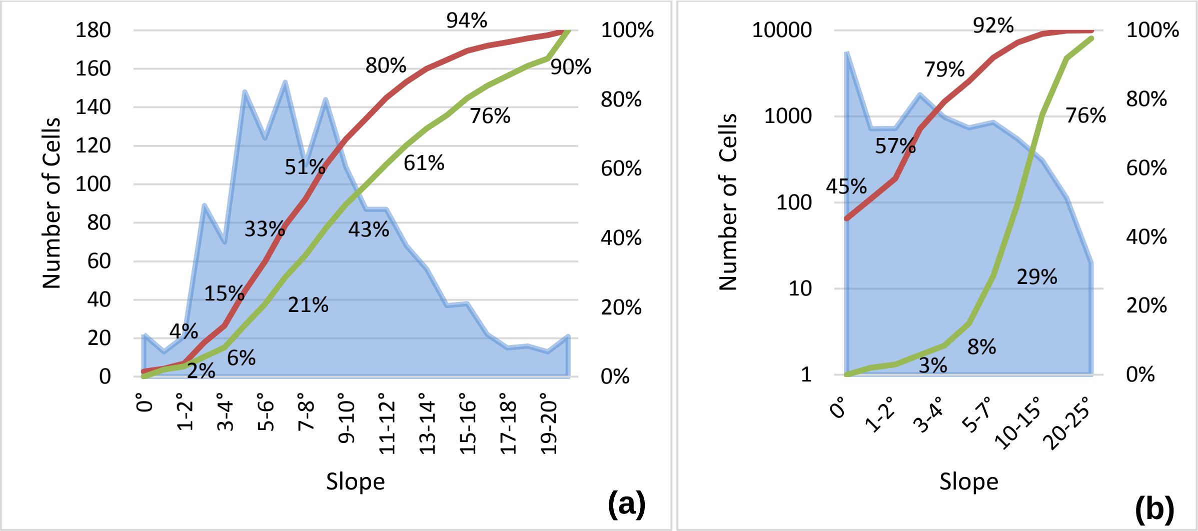

Figure 14 – **(a)** Graph of slopes of the blocks and boulders deposition zones in blue, their cumulative percentage in red and the slopes cumulative percentage of the entire debris flows transportation area in green. **(b)** Graph of slopes of the fine sediments and vegetation deposition zones in blue, their cumulative percentage in red and the slopes cumulative percentage of the entire debris flows transportation area in green.

Finer material area deposition is comprised on slopes between 0 and 7° to 92% of the total area of this sediments type (**Figure 14b**). The other 8% are on slopes up to 15°, but this may be photointerpretation mistakes or even DEM errors since they are located only at the E-SE edges of the demarcated area.

Consequently, we suggest using values between 0 and 7° with a good index of reliability for binary fine sediments area delimitation (**Figure 15a**), almost as the manual itself treats the mapping but including slopes between 0 and 2°. While using different hazard classes we can classify as high values between 0 and 2°, medium among 2 and 5° and low between 5 and 10°, that represents 57%, 85% and 96% cumulative percentage of the considered inundated area, respectively (**Figures 14b** and **15b**). This considers obviously the drainage distance and the deposition area morphology. It is important to note that in the studied case an important highway and a bridge (which was destroyed in the event) limited the reached area to be greater northwards.

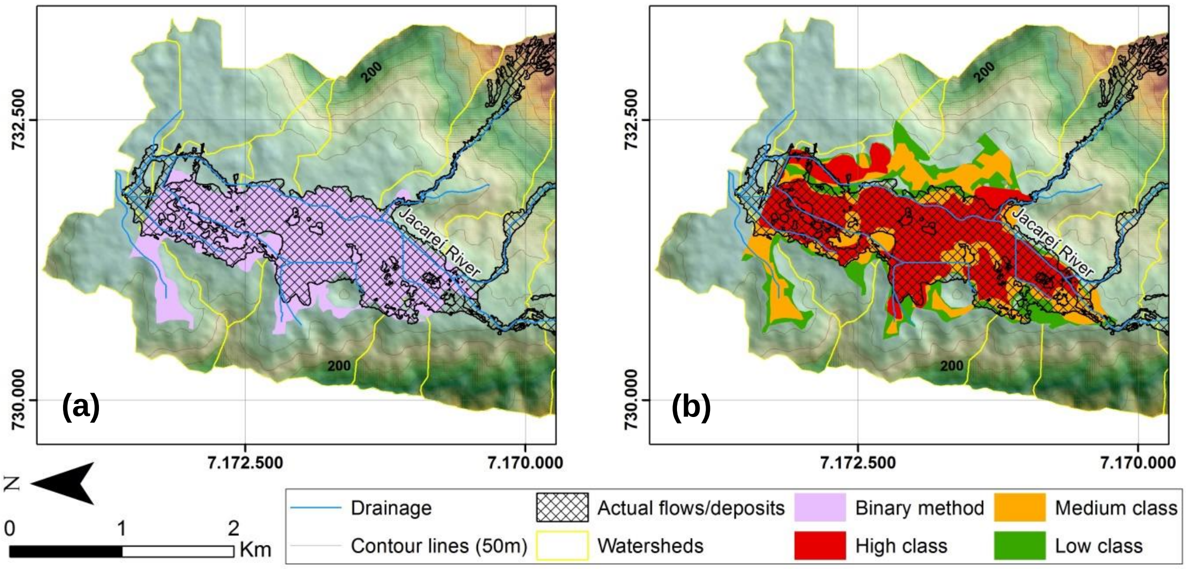

Figure 15 – Hazard maps showing the predicted reaching areas made from the proposed procedures for the deposition area for fine sediments. **(a)** Map using the binary method. **(b)** Map with the different hazard classes. The resulting maps are compared with the actual debris flows of the 2011 event. Horizontal datum SIRGAS2000, UTM zone 22S.

The maps suggested above were produced and showed that the one with three classes has an increase of the areas considered false positive and negative without the same increment on the true positive. In other words, **Figure 16** illustrates the quality loss proportion from high to low susceptibility classes associated to the real event. The graph shows smaller values as a better representation of the event truth. This may reflect the actual data concentration on the “slope core”, that is, the values between 0 and 2° and the high importance of this slope interval.

Despite its simplicity, the binary map has better results as it has smaller values on **Figure 16**. It takes a very good slope interval with a false negative area of only 14% of its total area, false positive of 27% while a true positive that covers 84% of the total finer material dispersion area. But for both maps, we considered the highway as an artificial barrier to the flow passage, what is not totally true on the reality. However, this is not a major problem as the area after these bound represents only 6.6% of the total dispersion area treated here.

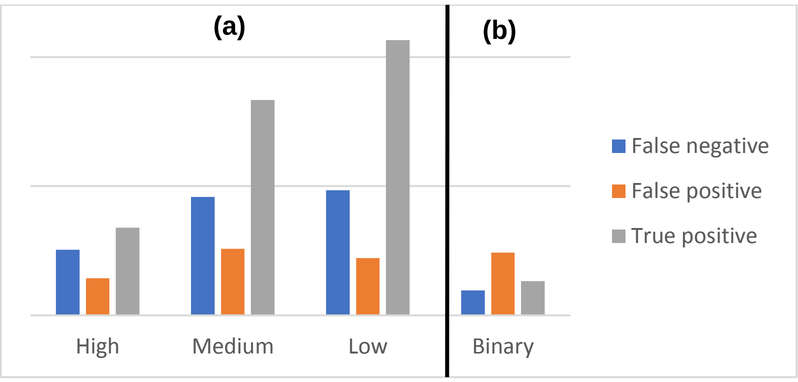

Figure 16 - Fine sediments and vegetation deposition zones analysis for **(a)** the three classes form and **(b)** the binary form (prone or not). It is shown on a unidimensional unity to compare form (or class) maps efficiency based on how low is the value in a log scale.

2.4.3. OTHER MORPHOMETRIC ANALYSIS (IPT/CPRM)

Several interactions of different morphometric indexes were performed testing which had good correlation and would be best to propose as an upgrade on the GIDES method (**Table 2**). These tests follows the premise that the watersheds with debris flows on 2011 are models to test the others from the same region we could notice what parameters or indexes discriminates these basins from other without this type of mass movements.

At this point, the goal is not to find exactly where the flow will initiate or pass through, but the watershed prone to debris flows occurrence. Once the valley confinement rule does not work well to discriminate prone to debris flows basins, the use of general morphometric analysis can highlight the basins which should or should not be further studied and mapped.

The first attempt was to use the IPT/CPRM procedure described above by Corsi et al. (2015) where it discriminates morphometric parameters of basin distinction (relief or topographic range, area and Melton index). The map using strictly their morphometric method showed total coherence with the reality as it marked all the watersheds truly affected by debris flows at the 2011 events as hazardous (**Figure 17**).

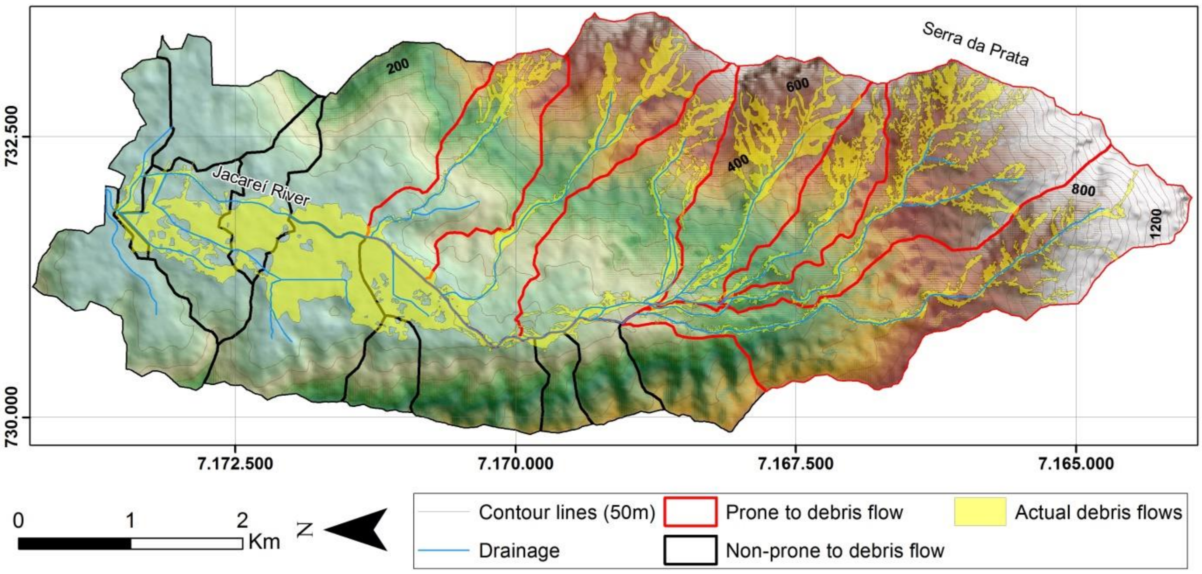

Figure 17 – Map produced using the IPT/CPRM method with its basins classification and the actual debris flows and deposits from 2011. Horizontal datum SIRGAS2000, UTM zone 22S.

One of the prerequisites to consider if a basin is prone to debris flows is that it has to be smaller than 10 km², and all of the studied watersheds are within this limit. So the other two parameters were used.

In order to confirm and perhaps to get a stronger morphometric relation, we compared the attributes' relation proposed by Corsi et al. (2015) with other ones proposed by different authors resumed in **Table 2**. From the several tested attributes and their correlations, the best that discriminate debris flows prone basins from the ones not prone are the basin's length, maximum altimetric difference, and Melton index, as can be seen in **Figure 18**. It also shows that the correlation between altimetric difference and length ($R^2 = 0.831$) is stronger than with Melton index. However it also is possible to distinguish watersheds with and without debris flows by using also Melton index, even if the boundaries among them are much smaller than using altimetric differences. In all of the three graphs is possible to segregate zones for debris flows prone basins based on the studied case.

A similar analysis was performed crossing those three parameters and the area with debris flow transportation, deposition, fine material deposition, and scars. But there is no direct correlation between them, that means these areas percentage on the watershed do not increase or decrease at the same manner with changes of the cited parameters. So it was not possible to distinguish how big would be an event only based on the correlation of those factors.

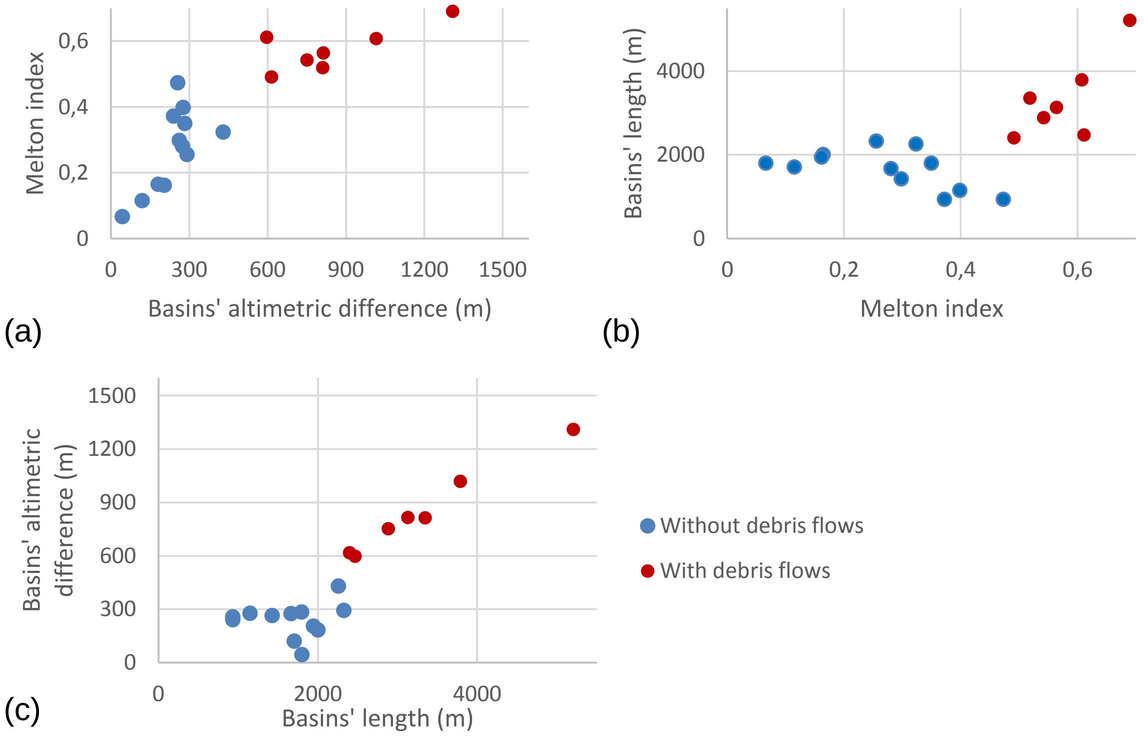

Figure 18 – Correlation between the best discriminating morphometric parameters from the 19 studied watersheds: **(a)** Melton index (y axis) and altimetric difference (x axis) as proposed by Corsi et al. (2015), **(b)** basin length (y axis) and Melton index (x axis) and **(c)** altimetric difference (y axis) and basin length (x axis).

2.5. DISCUSSION

As seen on March 2011, this region gathered all the basic elements to generate debris flows: high altitude gradients, high sediment amounts availability and an uncommon triggering rain episode. On some riverbanks, ancient debris flow deposits are recorded with several meters in height. Analyzing them, it is possible to conclude that events like this are recurrent. They have high magnitudes and also long frequency intervals because they lack historical records. There is no other debris flow register on historical ages at the region, only flash floods (Picanço et al., 2017). Despite low frequencies, they may have high impacts and volumes. These deposits are characterized by imbrication of blocks and boulders with low content of finer matrix.

The GIDES technique is in agreement with the international studies trend on debris flow prediction mapping. It considers mainly topographic criteria and basin morphometry for the critical and potential areas calculation (Wilford et al., 2004; Hungr, 2014). For the study case, after testing the GIDES method (CPRM, 2018) the results showed here evidences that it needs some improvements to fit the produced hazard zones to the mapped reality.

The first difficulty in the accurate determination of critical and dispersion areas is due to using the prior to the event drainage outline. When using prior to the event drainage as a reference, there is a great difference on rivers position, especially in the lowest altitude slopes or shallow channels. This movement was verified up to a few hundred meters, which clearly could cause great imprecisions to any type of debris flow prediction modeling or mapping (**Figure 19**). These rapid river channel alteration by debris flows is also discussed in Ge et al. (2014) where rivers in China were described to move laterally from 8 to 20 meters or more.

In unconfined (or semi-confined) valleys this is a considerable problem since one of the premises of these types of maps is to consider the already established drainage as an almost obligatory flow path (Hungr et al., 2014). It is an important matter once that most part of the population within the studied basin lives in this area, in other words, the map seems to be less accurate where most people live.

The transference of using the same 5 meters topographically higher than the channel value from the Japanese to the Brazilian reality was not the most appropriate, at least to the investigated case. The manual seems to be written based on a user that should work with physical means like paper maps and pencils, so we tried to propose more precise methods using digital platforms as GIS. This resource brings a more accurate map and closer to the reality of each track at individual watersheds. There are no technical reasons to generalize debris flows height values once, as shown before, they can reach up to 10 meters at the studied area instead of 5 meters and it is also possible to individualize this number for each drainage track.

Figure 19 – Satellite images showing the high mobility of the Jacareí river at May-2006 (above) and September-2012 (below). The light blue line is the river before the event and the dark blue line represents the river after the event for both images.

The manual itself states that the method's adaptation faces a series of limitations due to the "inexistence of a technical standard regarding the resistance of the building to mass movements and the small amount of data used to define the topographic conditions adopted to identify the areas of potential hazard" (CPRM, 2018).

At Jacareí basin the deposition areas slopes are divided into blocks and boulders zones with deposition concentrated at more than 90% between 3 and 16°, or 54% between 4° and 10° (**Figure 14a**) and finer sediments and most tree trunks area ranging from 0 to 7° for 92% of it (**Figure 14b**). For D'Agostino et al. (2010) the debris flows started to deposit at slopes of 10° and are completed deposited at less than 4° but considering their geologic conditions it is only possible to correlate these number to the blocks zone with very good similarities. There is also some concordance with the results from Fannin & Rollerson (1993) that attributes deposition on slopes with less than 20°.

Discriminating slope angles for debris flows and fluvial deposits is not easy on the same event with both deposits. But Watts & Cox (2010) apud Kritikos & Davies (2014) found 4° to be the limit between those different fans in New Zealand while De Scally & Owens (2004) concluded this limit should be 7.5° studying in the same country but in a different location. These studies show the non-uniformity for different sediment size zones. It is probably impossible to reach a worldwide or even a national wide slope angle range to distinguish those depositional patterns in an objective way. The composed material and the environment vary enormously.

Despite the GIDES method does not consider debris flows feeding landslides, there is a slope distribution from 11 to 35°. The average is 23.6° with limits given by one standard deviation of 17 and 30°. These results are slightly different from the literature which is varying mainly between 30 and 42° (Chen & Yu, 2011) or more than 30° (VanDine, 1985). However it is comparable with other studies with debris flows' initiation slopes between 20 and 45° (Jakob & Hungr, 2005). Particularly with one of the three analyzed basin types of Zimmermann (1990) that ranges from 13 to 33° and more than 25° for VanDine (1996), but it says that this slope can decrease with the increase of the basin's area.

Additionally, as we compared all resulting maps with the modified inventory map from Geoplanejamento (2011) it is important to have its uncertainties in mind. The main one is about its production. As a map produced basically from satellites images, it has the interpretation subjectivity and digitalization from the person who is making it.

Unfortunately, it was necessary to use some subjectivity, uncertain or imprecision when making these maps because the first result was in raster file format and its transformation into a polygon shape was made by hand, once the automatic tool offered by ArcGIS did not bring good results. One example of this subjectivity is on the delineation of the transition area between the channel and the deposition basin. It has some different possibilities for making this connection only taking into account the high class fine material dispersion. It was not clearly marked on the generated map or might represent deposition areas of bigger blocks and boulders and could explain part of the false positive indexes. GIDES Manual (CPRM, 2018) and Yin (2017) also agree that as the spatial resolution improves, the results tend to be better.

It is necessary to take into account the DEM spatial resolution. As GIDES Project seems to be a method widely used in Brazil, it would need to work well with relatively low resolution DEMs (i.e. 30 to 12.5 meters) that are widely available for great part of the territory for free. Creating a method that requires high resolutions would be unfeasible given the country's current reality. Moreover, it was obviously necessary to use models from images acquired before the event to preserve the original terrain morphology to bring reliable measurements. While not tested in this study, if available, the use of DTM (Digital Terrain Model) or even contour lines from topographic maps in a good scale could result in a better product than using DSM (Digital Surface Model). The reason is that the last one is a model with the vegetation and buildings while the others take into account only the ground, what really interest for geomorphometry studies along with data quality (Szypuła, 2017).

It is important to consider also that the studied event had the occurrence of several debris flows on a single episode. This fact increases the case complexity and is not covered by the GIDES proposed method. Ministry of National Integration (2018) cites that on Japanese studies basing GIDES procedure is uncommon the occurrence of diverse debris flows at the same time at the same catchment, different from the studied situation where a flow can interfere on another and dramatically change their behavior.

The GIDES procedure has a significant limitation as it was made to simulate only one single event at a time. The studied case brings the challenge of modeling the reaching zone of several debris flows happening concomitantly or temporally very close. This fact can change all the landscape and conditions of the previously estimated scenario. It represents a substantial problem for modeling flows in complex basins with debris flows intercrossing possibilities.

Another important issue when working on highly vegetated areas is to consider the importance of the vegetation role on debris flow behavior and volume estimation (Ministry of National Integration of Brazil, 2018). At the studied case we noted that vegetation of big dimensions (including whole tree trunks with more than 15 meters length) was also transported with finer material and can reach a wider and farther area than a debris flow composed only by blocks and boulders. Probably these woody materials comprise important volume because of the studied debris flow origin. They came from several translational landslides on a dense vegetated area.

The density of this large amount of biological material changes the flow's rheology and behavior, which becomes very different of a debris flow completely composed of rocky sediments. Since they are less dense, this woody material tends to reach greater distances. In the Jacareí river basin, it was observed that large logs were taken at same distances of sandy sediment. This makes the destructive power of this type of debris flow much bigger than debris flows only with a rocky composition.

Because they are complex processes, the GIDES manual seems to use a more simplified terminology where the traditional term debris flow would be applied to the whole process. In certain events, it can travel from an actual debris flow to debris flood, flash flood or hyper-concentrated flow. Although, since all of them occur in previously known paths, usually as valleys, thalwegs and first and second order channels, mapping the hazard to the debris flows occurrence is different from other types of gravitational mass movements (Hungr et al., 2014).

The differentiation between debris flow, debris flood, and flash flood basins would be an important improvement as the GIDES manual only works with the first one. As said by Wilford et al. (2004) debris flows can have a peak discharge of up to 20 times greater than debris floods, what is directly related to its energy and destruction force. They also use different values of morphometric attributes to make this distinction and Melton index and watershed length was the best association found followed by Melton index and relief ratio, what we call here as altimetric difference (Corsi et al., 2015). At Jacareí river basin, we conclude that associations of Melton index, altimetric difference and/or length guided to good results to discriminate only if a basin is debris flow prone or not, not including debris flood. More studies are necessary on other locations with debris floods occurrence in order to create a more detailed regional hydrogeomorphic processes classes boundaries.

As the confinement rule does not work on the studied case and might not work on many other semi or non-confined basins. It is proposed to use the relation of altimetric difference, watershed length and Melton indexes to determinate what watershed is debris flow prone or not. They are simple and easy to obtain parameters and proved to be efficient at the studied case.

Morphometric analysis on a smaller scale, in a several basins scale, can be very useful on the initial mapping level. It can distinguish watersheds that should be studied further in more details. It describes if an event might occur, and GIDES determinates where it can reach. So the use of the GIDES method associated with the IPT/CPRM procedure tested and improved here can be useful as a more effective mapping method.

More research in in other basins with similar characteristics is indispensable to confirm it and improve its robustness. But is important to emphasize that the IPT/CPRM method is not a watershed scale mapping method by itself. It needs to be combined with another more detailed one. Techniques like these cannot offer information about frequency and magnitude and require more details (Corsi et al., 2015). And once again DEM quality and spatial resolution are very important to assure a good map.

Any mapping method application needs to be analyzed by its operation, advantages, and limitations. Most of the above discussion is focused on the GIDES Project's limitations. It does not consider several important input features that could improve its results. Other mapping or modeling techniques use input parameters as hydrological models (Horton et al., 2013) or debris flow volume estimation (Berti & Simoni, 2014). But these inputs could also put an end to one of the main characteristics of the GIDES procedure: its simplicity. This feature probably comes from its origin as an empiric method. Thus, it must be widely tested because proposed values and attributes need to be verified as efficient on a large-scale, not only on the studied case of Serra da Prata.

The GIDES manual suggests an empirical mapping method. This type of procedure gets better as many values, tests and users it has. But it was tested for debris flows in just a few Brazilian cases (CPRM, 2018). The outcomes brought by this study are collaborating to validate the technique and also propose some improvements. Nevertheless, it is temerarious to affirm that the suggestions given here are more correct than the GIDES original form because it was generated from the events of the Serra da Prata and compared with the same events. So, obviously, it would fit better than the original form that was created with data from different places in Brazil and Japan. It is fundamental to make tests in other locations to confirm what we state here since an empirical method must be checked several times.

As told before, the independence of important parameters for debris flows studies such as rainfall volume, mobilized material volume, soil thickness, geology, flow rheology, debris composition, water concentration, content of fines, etc. (Berti & Simoni, 2007) can attribute less reliability, but turns it into a more practical, fast, easy and economical method. Perhaps if geotechnical parameters were introduced in the method at the first mapping stage there would be greater consistency with respect to the expected reach area. But the GIDES manual only considers it in a posterior phase. The next step after the spatial distribution is the hazard degree qualification (from P4 to P1). It is based on the observation of terrain instability evidences in normal rain conditions only to the critical area. Dispersion areas will necessarily assume one hazard degree less than the critical area.

The manual says these evidences for debris flows are the local disasters history, deposits of ancient events, river banks slope, watershed area and the deposited material thickness in the channel. The simple fact of debris flow occurrence is enough to classify the critical area as very high hazard (P4) and the dispersion area as high (P3), such as the studied case. The manual also defines that the hazard classes refer to “a normal rainy season, that is, they do not apply to extreme weather conditions” (CPRM, 2018). But the studied case did not take place in a normal rainy episode, like many others in Brazil.

After all, it is suggested as a final method a mixture of what we think that would be the best of each tested and proposed procedures and values for the debris flows hazard mapping using the studied event as a premise. Instead of using the GIDES Project prerequisites, we believe that basins’ morphometric attributes as altimetric difference, length, and Melton index can differentiate more efficiently watersheds prone or not to debris flows using the IPT/CPRM method and our improvement suggestions. At the critical area, the more accurate, detailed and individualized results are on the maximum perpendicular to the channel slope-maximum debris flow height relation. Good accordance was not found on blocks and boulders deposition area out of fans on the tested methods. Otherwise, the dispersion or deposition zone on the fan area has the best results from the maps for fine sediments regions when using the binary form that considers slopes of 0 to 7° as deposition zones.

2.6. CONCLUSIONS

Detailed ways of demonstrating debris flows hazard areas depends on how map producers see the relationships between true positives and false negatives and positives and its benefits and disadvantages. This equation depends much on the concepts, visions, and experiences of each one to equalize how conservative the map should be since unfortunately these proposed methods present (in different proportions) increments in the false as the trues advance even more.

GIDES manual needs to have some way of verifying whether the generated map has reliability, whether it is correct and how accurate. This is important because the operator will know if it has the required reliability so that it can be applied or not.

The contribution of this work is on the procedures of the GIDES Project testing and validation. Suggestions for improvements could be of great value in a technique intended to be nationally used because the originally proposed form may have been excessively restrictive and determinative.

Values and equation were proposed in this work to correlate several factors or attributes of the basins in order to classify them or to map the possible debris flows in a more objective and practical way. After the needed validation and testing in other locations, they could assist technicians in the arduous responsibility of differentiating sites hazardous or not to debris flows.

It is important to notice that these proposed methods were tested only at one location and more tests are imperative to prove that it really works widely. Additionally, the discussion among maps made from binary models is not complete if we do not put it in practice. There is a problem when local public administrators and population have a type of blind faith in binary maps once they appear to have only areas totally safe or totally unsafe without intermediate values. This issue could be partially surprised using the different classes' method because these wider values range is possibly closer to the real world cases. The classes division is also a demonstration of the assertiveness or map probabilities reflecting greater credibility and flexibility in its practical application by the government agencies.

The debris flow hazard maps from the Jacareí river basin area generated in this study may help residents and authorities to take more accurate and reliable precautionary measures. Results bring many mapping possibilities for different scales, debris flow sections and their behaviors. It is possible to use them together or separately depending on the studied region. This study shows that the GIDES Project presents a promising technique, but also has points that can be improved by the partial use of other procedures and values, besides tests in different locations.

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