UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
INSTITUTO DE GEOCIÊNCIAS
PROGRAMA DE PÓS-GRADUAÇÃO EM GEOCIÊNCIAS

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ORIENTADOR - Prof. Dr. Iran Carlos Stalliviere Corrêa
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*A morte, além da saudade, deixa obras inacabadas.*

*Ao Professor Dr Ricardo Norberto Ayup Zouain (In Memoriam) ainda muito vivo em nossa memória, dedico essa tese.*

***"Faça o que tiver que fazer com toda tranquilidade, chegará igual, mais cedo ou mais tarde. O que você deve saber principalmente é que tem um enorme potencial e realmente é excelente naquilo que faz e que está desenvolvendo. Se não acreditasse nesse potencial, não estaríamos fazendo todo este esforço juntos!!!."***

***Ricardo Norberto Ayup Zouian***

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## RESUMO

A caracterização morfométrica e hipsométrica de bacias hidrográficas permite o melhor entendimento do seu funcionamento enquanto sistema, facilita a correlação com suas características e potencializa diversos estudos. O emprego de métodos quantitativos e qualitativos para caracterizar uma bacia hidrográfica possibilita uma maior compreensão da sua dinâmica e por isso o emprego de vários parâmetros é fundamental. Nessa tese é apresentada a análise morfométrica e hipsométrica e a determinação automática de hidrografia e knickpoints na bacia da Lagoa Mirim, uma bacia transfronteiriça, localizada na costa atlântica da América do Sul entre os paralelos 31°S e 34°30'S e entre os meridianos 52°W e 55°30'W, com 58407.78km$^2$ de área, dos quais 47% estão em território brasileiro e 53% em território uruguaio. A análise e obtenção dos parâmetros e a determinação automática de hidrografia e knickpoints na bacia da Lagoa Mirim, foi realizada com técnicas de Geoprocessamento, utilizando as ferramentas de análise espacial e de manipulação de dados do programa ArcGis, versão 10.2.2. Foram utilizadas 15 imagens SRTM (Shuttle Radar Topographic Mission), com resolução espacial de 1 segundo de arco (1"), aproximadamente 30m, para gerar o Modelo Digital de Elevação (MDE) da área de estudo. Este modelo foi validado com levantamento cinemático GNSS (Sistemas Globais de Navegação por Satélite), pós-processado com o método de Posicionamento por Ponto Preciso (PPP). As análises morfométrica e hipsométrica e a determinação da hidrografia e knickpoints da Bacia da Lagoa Mirim foram realizadas a partir do MDE SRTM. A hidrografia foi obtida com o Model Builder e ferramentas hidrológicas do ArcGis. E os knickpoints foram determinados através do Knickpoint Finder, um script em linguagem Python integrado ao ArcTollBox do programa ArcGis. Os resultados demonstram que a utilização de dados SRTM em ambiente SIG (Sistemas de Informação Geográfica) permite a caracterização de bacias hidrográficas, sendo útil para gestão e gerenciamento dos recursos hídricos e para estudos ambientais, mostrando-se uma alternativa prática e viável ao minimizar custos e tempo na execução dos trabalhos.

**Palavras-chave:** SIG; SRTM; GNSS; Knickpoints;

## ABSTRACT

The morphometric and hypsometric characterization of river basins allows a better understanding of its functioning as a system, facilitates the correlation with its characteristics, and potentiates several studies. The use of quantitative and qualitative methods to characterize a river basin allows a better understanding of its dynamics, therefore the use of several parameters is fundamental. This thesis presents the morphometric and hypsometric analysis and the automatic determination of hydrography and knickpoints in the Mirim Lagoon Basin. Mirim Lagoon basin is a transboundary basin, located in the Atlantic coast of South America, between parallels 31°S and 34°30'S and meridians 52°W and 55°30'W, with an area of 58,407.78 km$^2$, being 47% in Brazilian territory and 53% in Uruguayan territory. The analysis and acquisition of morphometric and hypsometric parameters and the determination of hydrography and knickpoints were performed with geoprocessing techniques, using the spatial analysis and data manipulation tools of the software ArcGIS, 10.2.2 version. We used 15 SRTM (Shuttle Radar Topographic Mission) images, version 3, band C, with a spatial resolution of 1 arcsecond (*1*"), approximately 30 meters, to generate a Digital Elevation Model (DEM) of the study area. This model was validated by means of kinematic GNSS (Global Navigation Satellite System) survey post-processed using the Precise Point Positioning (PPP) method. The intended morphometric and hypsometric analysis and the determination of hydrography and knickpoints of Mirim Lagoon basin were performed using the DEM SRTM. The hydrography was obtained with the Model Builder and the hydrologic tools of ArcGis. And the knickpoints were determined using the Knickpoint Finder, a script in Python language integrated to ArcGis ArcToolbox The results show that the use of SRTM data in GIS (Geographic Information Systems) allows the characterization of the watersheds, which is useful for water resources management and for environmental studies, and prove to be a practical and viable alternative to minimize cost and time in the work execution.


**Keywords:** GIS; SRTM;GNSS;Knickpoints.

**SUMÁRIO**

# ESTRUTURA DA TESE

Esta tese de doutorado está estruturada em formato de artigos científicos submetidos em periódicos. Consequentemente, sua organização compreende as seguintes partes principais:

Introdução, onde é apresentada a localização da área de estudo, o contexto geológico simplificado, uma abordagem sobre o estado da arte, procurando caracterizar os principais trabalhos desenvolvidos sobre o tema, a problemática e justificativa para aplicação dos métodos empregados para o desenvolvimento da tese e a síntese integradora a qual é composta por uma análise resumida e integradora dos dados obtidos nesta tese, salientando as suas contribuições para o aprimoramento do conhecimento científico da região de estudo.

Os itens seguintes consistem no corpo principal desta tese, onde são apresentados os artigos submetidos a periódicos com corpo editorial permanente e revisores independentes, com autoria principal do doutorando e colaboradores (incluindo orientador e coorientadora) durante o desenvolvimento de seu Doutorado. Nestes artigos são apresentados os resultados obtidos no decorrer do desenvolvimento da tese bem como a avaliação e a interpretação dos dados com discussão e conclusão.

# 1. INTRODUÇÃO

A análise de bacias hidrográficas começou a apresentar caráter mais objetivo a partir de 1945, com a publicação de Horton (1945) que procurou estabelecer as leis de desenvolvimento de rios e de suas bacias e abordou quantitativamente as bacias de drenagem e seu estudo serviu de base para a concepção metodológica e originou inúmeras pesquisas por parte de vários seguidores (Christofoletti, 1980).

A bacia de drenagem é uma unidade básica na investigação morfométrica porque todos os processos hidrológicos e geomórficos ocorrem dentro da bacia hidrográfica, onde os processos denudacionais e agradacionais são explicitamente manifestados e é indicado por vários estudos morfométricos (Horton, 1945; Strahler 1952, 1964;Hack,1957,1960,1973; Shreve,1966,1969; Evans 1972; Chorley 1969;Chorley et al., 1984, 1957; Merritts e Vincent 1989; Merritts et al.,1994). A descrição das bacias de drenagem e redes de canais, com base nas contribuições feitas por Horton(1932,1945) e complementadas por Chorley (1957), Melton (1965,1957,1958), Miller (1953), Schumn (1956), Strahler (1964), Powell(1975) e outros, passou de um estudo puramente qualitativo e dedutivo para uma rigorosa ciência que fornece valores numéricos que podem ser aplicados na prática.

Diversos estudos abordam a análise dos parâmetros morfométricos, destacando-se os trabalhos realizados por Schumm (1956,1977,1993,2002), Christofoletti (1969), Horton (1945), entre outros. Pareta (2011) analisou a Bacia de Yamuna, India com modelos digitais de elevação e técnicas de Geoprocessamento. Rai et al. (2017) fizeram uma abordagem baseada em SIG (Sistemas de Informações Geográficas) com o uso de MDE (Modelos Digitais de Elevação) e analisaram a Bacia do Rio Kanhar, na Índia. Abboud e Nofal (2017) analisaram a morfometria da Bacia Wadi Khumal, na costa oeste da Arábia Saudita, usando usando técnicas envolvendo Sensoriamento Remoto e SIG. Aher et al. (2014) usaram uma abordagem envolvendo Sensoriamento Remoto e SIG(Sistemas de Informações Geográficas) para a quantificação da caracterização morfométrica para gestão nos trópicos semi áridos da Índia. Ahmed e Srinivasa (2016) analisaram a hipsometria da bacia Tuirini na Índia; Ahmed et al. (2010) realizaram um estudo na sub-bacia em Karnataka.

Na década de 1980, o desenvolvimento do Sensoriamento Remoto com radares interferométricos e a criação e implementação de ferramentas computacionais com interface mais amigável aos usuários, associado a um novo momento científico das Geociências, possibilitou o uso de técnicas de mensuração "à distância". Essas técnicas contribuíram para o desenvolvimento de ferramentas computacionais para o tratamento da informação geográfica, os chamados Sistemas de Informação Geográfica (SIG). Isso, consequentemente, foi consolidado por estudos de caráter científico realizados nas áreas da Cartografia, Geologia, Geografia, Geomorfologia, dentre outras, e em pesquisas desenvolvidas nos setores público e privado para planejamento e gestão territorial de suas atividades. Desde então, a Geomorfologia passa a ser marcada pelo uso de técnicas quantitativas. Mas, independente da renovação conceitual e metodológica, o objetivo geral permanece o mesmo: estudar e interpretar as formas do relevo terrestre e os mecanismos responsáveis pela sua modelagem, em todas as suas escalas de análise, desde modelos de escala global até em nível local.

A análise e a modelagem de sistemas geomorfológicos em ambiente computacional potencializaram a obtenção e análise de dados e informação que antes demandavam dispendiosos e longos levantamentos de campo e gabinete, como é o caso da análise morfométrica de bacias hidrográficas. A análise morfométrica tem como objetivo quantificar atributos do relevo para classificá-lo e comparar o modelado e a evolução em áreas de contexto climático (exógeno) e estrutural (endógeno) diferentes (Horton, 1945; Strahler, 1954; Schumm, 1956; Strahler, 1957; Hack, 1960; Christofolleti, 1980).

Uma das tecnologias utilizadas na análise de sistemas geomorfológicos é o tratamento computacional de dados obtidos por sensoriamento remoto, principalmente os dados fornecidos por radares interferométricos, a exemplo daqueles provenientes da SRTM (Shuttle Radar Topography Mission). Estes dados permitem gerar um modelo topográfico para toda a superfície terrestre e podem servir de base para estudos em diversas unidades de análise geomorfológica (sistemas geomorfológicos), tais como uma bacia hidrográfica.

A técnica mais comum de derivação de atributos morfológicos do relevo em ambiente digital é a partir do uso dos Modelos Digitais de Elevação (MDEs) e da rede hidrográfica digital. Sobre esses dados são aplicadas rotinas computacionais para extração de parâmetros morfométricos. Os MDEs e as redes hidrográficas devem ter consistência morfológica e hidrológica para que os resultados obtidos nas análises morfométricas sejam válidos. O uso de MDEs para representar o relevo e derivar a rede de drenagem foi ampliado desde a disponibilização de bancos de dados altimétricos obtidos por sensoriamento remoto, mais especificamente aqueles gerados por imageamento via interferometria radiométrica.

A Geomorfometria, definida como a ciência da descrição e de análise quantitativas das características geométrico-topológicas da paisagem (Pike, 1995,1998; Pike e Wilson, 1971;Pike et al., 2009; Bettu et al. 2013), tem como um de seus principais objetivos o desenvolvimento de métodos de classificação objetiva e replicável para as formas de relevo, fornecendo indicadores a respeito dos processos geomórficos atuantes no relevo a partir de dados de sensores remotos. O conceito básico da Geomorfometria é a parametrização morfométrica, derivada geralmente de um MDE, incluindo informações específicas a respeito da forma da superfície terrestre (Wilson e Gallant, 2000; Smith,1956;Smith et al., 2008; Bettu et al. 2013). Wilson e Gallant (2000) classificam os parâmetros morfométricos em primários (obtidos diretamente do DEM, como a declividade e a curvatura) e compostos (calculados a partir de parâmetros primários, como o índice topográfico).

A hipsometria e a morfologia do relevo, bases da Geomorfometria, resultam de interações complexas entre litologia, tectônica, clima e processos erosionais, o que a torna de suma importância nos estudos geomorfométricos para as ciências da Terra. Assim, descritores quantitativos das características do relevo e de sua estrutura são considerados índices essenciais para diferenciar as formas de relevo e servem de base para pesquisas quantitativas em Geomorfologia.

Em geomorfologia fluvial, o termo Knickpoint (Kp) ou ruptura de declive, aplica-se quando deparamos com secções subitamente íngremes no perfil longitudinal de um curso de água. A análise da sua posição e distribuição revela-se um marcador essencial para a interpretação da incisão da rede fluvial e da evolução das paisagens marcadamente dissecadas pela erosão fluvial (Ferreira, 2010). Deste modo, a reflexão sobre a distribuição dos knickpoints nas bacias hidrográficas constitui uma tarefa fundamental nos estudos que versam a evolução da paisagem, assumindo-se como um método essencial nos estudos de geomorfologia fluvial (Goudie, 2004; Ferreira, 2010;Hayakawa e Oguchi, 2006,2009; Crosby et al., 2006).

Segundo Florenzano (2008) o perfil longitudinal de um canal de drenagem expressa a relação entre a altimetria e o comprimento de um determinado canal nos diferentes pontos entre a nascente e a foz. Em geral, de forma parabólica, o perfil típico é côncavo (considerado em equilíbrio, ou seja, os processos de erosão, transporte e deposição estão em equilíbrio entre si.

Os cursos d'água são sensíveis às modificações tectônicas crustais, respondendo de imediato a processos deformativos. Nesse sentido, as técnicas que exploram atributos relacionados aos perfis ou ao traçado dos cursos d'água apresentam um elevado potencial para a detecção e avaliação de deformações (Etchebehere et al.2004;Volkov et al., 1967, Schumm, 1993).

Diversos estudos abordam a análise de drenagem para a identificação de anomalias, destacando-se os trabalhos piorneiros de Horton (1945); Strahler (1952); Howard (1967) e Hack (1973). Na atualidade, muitos autores publicaram trabalhos envolvendo a determinação de Knickpoints e anomalias no perfil fluvial, entre eles, Gardner (1983) apresentou um estudo experimental de knickpoints e perfis longitudinais. Seeber e Gornitz (1983) estudaram perfis de rios no ao longo do arco do Kimalaia como indicadores de atividades tectônicas. Keller e Pinter (1996) investigaram o levantamento tectônico nas Montanhas San Gabriel, sul da Califórnia. Etchebehere et al. (2004, 2006) aplicaram o Índice "Relação Declividade-Extensão – RDE" na Bacia do Rio do Peixe (SP) para detecção de deformações neotectônicas. Harbor et al. (2005) estudaram os Knickpoint nos Apalaches Centrais, USA. Bishop et al. (2005) estudaram os knickpoints e a área de captação de rios elevados no leste da Escócia. Crosby e Whipple (2006) estudaram a distribuição de Knickpoints nas redes fluviais, e encontraram 236 cachoeiras no rio Waipaoa na Nova Zelândia. Salamuni et al. (2013) aplicam a ferramenta knickpoint finder para a busca de geossítios de relevante interesse para o geoturismo. Nascimento et al. (2013) apontaram as evidências de atividade neotectônica na conformação do relevo da Serra do Mar, no estado do Paraná, Brasil, através da determinação de Knickpoints. Queiroz et al.(2015) analisam a drenagem com o software Knickpoint Finder, com aplicações em estudos de morfotectônica e neotectônica.

Neste contexto, a presente tese, cujos objetivos são caracterizar morfometricamente e hipsometricamente, bem como determinar, de maneira automática, a hidrografia e os knickpoints na bacia da Lagoa Mirim com a utilização de dados obtidos por levantamentos GNSS e imagens SRTM, apresenta uma contribuição à compreensão evolutiva desta bacia. Os resultados e análises estão descritos nos artigos integrantes desta tese.

## 1.1. Localização da Área de estudo e Contexto Geológico Simplificado

A área de estudo deste trabalho é a Bacia da Lagoa Mirim, localizada na costa atlântica da América do Sul entre os paralelos 31°S e 34°30'S e entre os meridianos 52°W e 55°30'W, correspondendo a uma área de 58407.78km$^2$, dos quais 47% em território brasileiro e 53% em território uruguaio, constituindo uma bacia transfronteiriça. O lado brasileiro envolve 20 municípios e o lado uruguaio 5 departamentos. Na figura 1 é apresentada a localização da Bacia Hidrográfica da Lagoa Mirim.

A Bacia da Lagoa Mirim é descrita na literatura como uma unidade paleogeográfica formada pela existência de grandes esforços extensionais que produziram fraturas pela erupção de lavas vulcânicas que permitiram o afundamento de extensas massas de rochas. Esses fenômenos tiveram início há 150 milhões de anos, quando houve a quebra do enorme continente Gondwana, e estão vinculados à abertura do que é hoje o Oceano Atlântico.

A área de inundação da Lagoa Mirim é resultado de processos de afundamento do Jurássico Médio e Superior que gerou a fossa tectônica desta lagoa. Durante o Cenozóico, o processo de afundamento contínuo e moderado, juntamente com os movimentos verticais lentos que ocorreram durante o Terciário e o Quaternário, originaram as baixas altitudes e os interflúvios mais elevados e extensos. A interação do desenvolvimento geológico com os elementos paleoclimáticos complexos, principalmente durante o Quaternário, resultou no relevo atual, representado pelos aplainamentos e inselbergs. A faixa de costa é resultado das transgressões marinhas, as quais deram origem à maioria dos banhados e das lagunas da costa formadas durante o Holoceno. O embasamento geológico da bacia hidrográfica é composto por uma complexidade de estruturas do escudo Sul-Americano. A zona ocidental é caracterizada por uma tendência orogenética positiva que, ao final do Cenozóico, originou a formação de relevos de baixas altitudes (morros e serras), atingindo, no máximo, 520 m. Na porção leste da bacia, os processos de intemperismo químico tiveram início no permocarbonífero até o Jurrásico, o que permitiu um acúmulo de sedimentos na faixa de costa. (Probides, 2000; Montaña e Bossi, 1995, Steike e Sato, 2008).

O embasamento geológico da bacia hidrográfica é composto por uma complexidade de estruturas do escudo Sul-Americano. A zona ocidental é caracterizada por uma tendência orogenética positiva que, ao final do Cenozóico, originou a formação de relevos de baixas altitudes (morros e serras), atingindo, no máximo, 520 m. Na porção leste da bacia, os processos de intemperismo químico tiveram início no permocarbonífero até o Jurrásico, o que permitiu um acúmulo de sedimentos na faixa de costa.

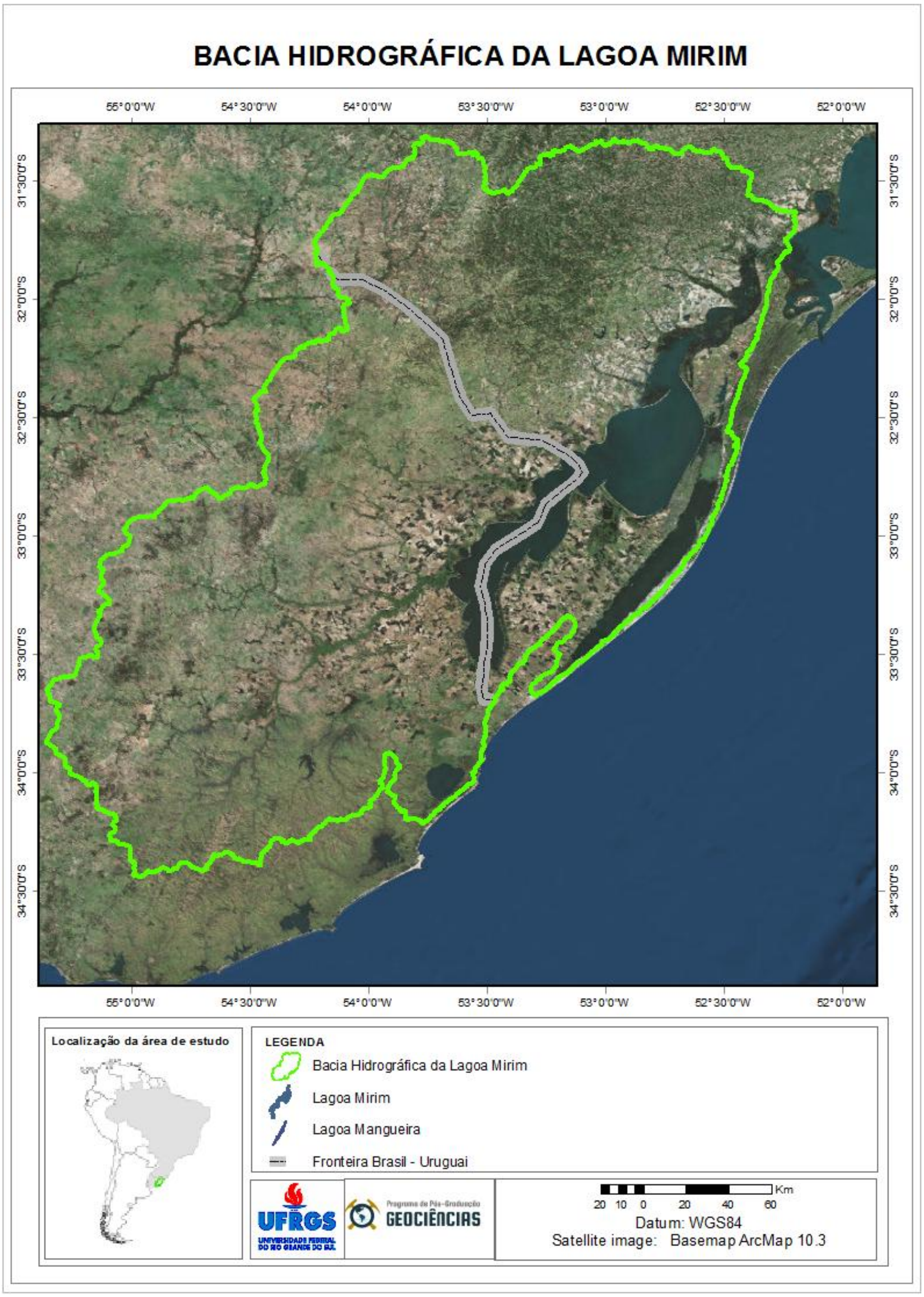


Figura 1 – Localização da Bacia Hidrográfica da Lagoa Mirim.

## 1.2. Problema Científico e Justificativa Metodológica

O objeto de estudo da presente proposta de tese é a determinação automática de Knickpoints e análise morfométrica e hipsométrica da bacia hidrográfica da Lagoa Mirim no contexto da evolução da paisagem. Para esse fim, o trabalho de pesquisa aqui desenvolvido trata da integração de informações geomorfológicas, cartográficas e geodésicas em um Sistema de Informações Geográficas (SIG).

No contexto da geomorfologia fluvial, a evolução da paisagem está relacionada ao estudo dos perfis de drenagem da bacia hidrográfica. Os conceitos de equilíbrio e de desequilíbrio dos perfis de drenagem estão associados aos knickpoints. A formação de knickpoints se deve a vários mecanismos, tais como variações do nível de base, deformações tectônicas e litológicas entre outros.

Consequentemente, o conhecimento da posição e da distribuição dos knickpoints nas bacias hidrográficas é fundamental para análise da evolução da paisagem, sendo que a identificação destes pontos se dá pela detecção de anomalias no perfil longitudinal dos cursos d' água (perfil de drenagem). O perfil longitudinal de drenagem representa a relação entre a variação altimétrica e o comprimento do rio, da nascente até a foz ou até a convergência com outro rio, e, portanto, para sua construção são necessários dados de altitude e da extensão do rio. A qualidade destes dados influencia diretamente a qualidade das análises realizadas.

O perfil longitudinal pode ser elaborado a partir de dados oriundos de cartas topográficas, a partir de levantamentos de campo clássicos ou geodésicos (GNSS), por métodos fotogramétricos ou por meio de sensores remotos, como imagens de satélites e dados fornecidos por radares interferométricos. O uso de Modelos Digitais de Elevação (MDE) para representar o relevo e derivar a rede de drenagem evoluiu frente à disponibilização de bancos de dados altimétricos obtidos por sensoriamento remoto, principalmente aqueles obtidos por imageamento via interferometria radiométrica. O banco de dados altimétricos mais completo e mais utilizado é o proveniente do SRTM (Shuttle Radar Topographic Mission).

Para avaliar a consistência hidrológica e morfológica dos MDEs SRTM e da rede hidrográfica derivada deles, é necessária a comparação com dados de maior precisão e acurácia obtidos de outras fontes como, por exemplo, de levantamentos geodésicos com GNSS. Além disso, a avaliação deve ser realizada em escala de análise compatíveis com os dados avaliados e de referência.

O problema de pesquisa tratado neste estudo é como realizar a determinação automática de knickpoints e a caracterização morfométrica e hipsométrica da bacia hidrográfica da Lagoa Mirim, utilizando técnicas de geoprocessamento, para analisar a evolução da paisagem.

Portanto, para a solução do problema em questão, esta proposta de tese se desenvolve e é formulada a partir da seguinte hipótese:

A evolução da área tem variáveis vinculadas aos efeitos da estruturação geológica, litológica e geomorfológica.

Define-se, assim, como objetivo geral, realizar a análise morfométrica e hipsométrica e a determinação automática da hidrografia e dos knickpoints da Bacia Hidrográfica da Lagoa Mirim a partir de dados obtidos por levantamentos GNSS e imagens SRTM.

A metodologia adotada envolve o levantamento GNSS cinemático pós-processado, o processamento de imagens SRTM para geração do MDE hidrologicamente consistente, a validação do MDE SRTM, a obtenção automática da hidrografia, o cálculo dos parâmetros morfométricos e hipsométricos e a determinação automática dos knickpoints da bacia hidrográfica da Lagoa Mirim.

A partir disso são estabelecidos os seguintes objetivos específicos:

- obter e validar um MDE a partir de imagens SRTM da região da bacia hidrográfica da Lagoa Mirim;

- determinar e analisar as características morfométricas e hipsométricas da bacia utilizando o MDE SRTM gerado e avaliar os resultados;

- determinar a hidrografia da Bacia da Lagoa Mirim, caracterizar os a hierarquização da drenagem e determinar a distribuição de Knickpoints na região de estudo.

- realizar a integração das informações cartográficas, geodésicas, hidrográficas e geológicas simplificadas em um Sistema de Informações Geográficas (SIG);

A presente tese abordou aspectos morfométricos, hipsométricos, cartográficos, geodésicos, hidrológicos e geológicos simplificados da Bacia Hidrográfica da Lagoa Mirim.

## 1.3 Síntese Integradora

O desenvolvimento do trabalho envolvendo a obtenção do MDE SRTM da bacia hidrográfica da Lagoa Mirim e a sua validação para aplicações em análises morfométricas, hipsométricas e hidrológicas integrado com a literatura descrita, revelou importantes aspectos concernentes à área de estudo no contexto da evolução da paisagem.

No artigo 1 intitulado “Validation of the Digital Model of Elevation (SRTM) with GNSS surveying applied to the Mirim Lagoon Hydrographic Basin” é apresentada a metodologia desenvolvida e os resultados das análises realizadas para validação da acurácia vertical do MDE SRTM de toda a bacia hidrográfica da Lagoa Mirim. As coordenadas tridimensionais dos 275916 pontos de controle foram obtidas pelo método de posicionamento cinemático com uso de receptor GNSS. Os resultados demonstraram que os erros verticais médios absolutos do conjunto de dados de altitude do MDE SRTM variam de 0,07m a ± 9,9m, com média igual a -0,28m e a correlação entre o MDE SRTM e o levantamento GNSS foi de 0,9995281, o que é melhor que o valor da precisão padrão indicada em sua especificação técnica, que é 16m, e valida o MDE SRTM para aplicações em análises morfométricas e hipsométricas, geomorfologia fluvial e estudos geológicos na área da Bacia Hidrográfica da Lagoa Mirim.

O artigo 2 intitulado “Morphometric and Hypsometric Analysis of the Mirim Lagoon Hydrographic Basin, Transboundary Water Resources Region” apresenta os resultados das análises espaciais realizadas para obtenção dos parâmetros morfométricos e hipsométricos, bem como para geração automática da hidrografia, da Bacia Hidrográfica da Lagoa Mirim, a partir de dados SRTM. A hidrografia gerada foi hierarquizada e foi definida a projeção cartográfica Cônica Conforme de Lambert com dois paralelos padrão determinados utilizando a constante de Kavrayskiy's. Os parâmetros morfométricos e hipsométricos foram calculados a partir de análises espaciais sobre o MDE SRTM gerado e de rotinas computacionais implementadas. A rede de drenagem da bacia é composta por 143969 canais, é classificada como de 9ª ordem (Strahler, 1952) e há um predomínio de canais de pequena ordem. O padrão de drenagem da bacia é dendrítico, o que indica ausência de controle estrutural ou tectônico, e o valor obtido para a relação de bifurcação média, corresponde a uma bacia de drenagem muito dissecada (Strahler, 1957). Com o índice de circularidade concluiu-se que a Bacia da Lagoa Mirim tende a ser mais alongada, favorecendo, assim, o processo de escoamento. Além disso, a bacia não está sujeita a grandes enchentes (Horton, 1932), conforme indicação do fator de forma e do coeficiente de compacidade, sendo que a baixa densidade de drenagem indica um subsolo permeável, com boa drenagem e capacidade de escoamento rápido (Strahler, 1957). O relevo da bacia, possui amplitude altimétrica de 513m e há um predomínio de valores abaixo de 8% para a declividade, a qual varia de 0 a 45 %. O valor da integral hipsométrica revelou que a bacia está em estágio de senilidade, onde está totalmente estabilizada.

E, finalmente, no artigo 3 intitulado “Automatic Determination of Knickpoints in the Mirim Lagoon Basin, region of cross-border hydric resources (Brazil and Uruguay, South America)” foram determinados automaticamente 594 knickpoints na bacia através do script Knickpoint Finder e a relação declividade extensão.

Foram apresentados o modelo digital de elevação, mapas de declividade, relevo sombreado e mapas geológicos simplificados, sendo possível encontrar a região de maior concentração e observar que essa concentração ocorre principalmente ao norte e nordeste da bacia, nas proximidades de suas cabeceiras, onde há maior amplitude de relevo e falhas geológicas.

A distribuição dos Knickpoints nos mapas geológicos e tectônicos simplificados, mostra que há grande correlação dos resultados encontrados nesse trabalho com a evolução da região da bacia da lagoa Mirim e com as falhas geológicas, diques e litologia da região de maior concentração dos knickpoints.

A evolução da drenagem está relacionada com a Geologia local, modelando o relevo a partir das orientações da rede de drenagem.

A metodologia desenvolvida, juntamente com as técnicas automáticas de geoprocessamento e scripts integrados em ambiente SIG com o uso de MDEs SRTM apresentadas nesta tese, mostraram-se eficientes no estudo de uma grande bacia hidrográfica. As análises e as representações são de grande importância em investigações hidrológicas, ambientais e geomorfológicas.

Todos os objetivos do presente trabalho foram atingidos com sucesso acima do esperado, por se tratar de uma bacia hidrográfica muito grande, em região plana, transfronteiriça, sendo necessária a compatibilização de datum e a definição de uma projeção cartográfica adequada.

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# 2 ARTIGO SUBMETIDO AO BOLETIM DE CIÊNCIAS GEODÉSICAS

## VALIDATION OF THE DIGITAL MODEL OF ELEVATION (SRTM) WITH GNSS SURVEYING APPLIED TO THE MIRIM LAGOON HYDROGRAPHIC BASIN.

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# Validation of the Digital Model of Elevation (SRTM) with GNSS surveying applied to the Mirim Lagoon Hydrographic Basin

*Validação do Modelo Digital de Elevação (SRTM) com levantamento GNSS aplicado à Bacia Hidrográfica da Lagoa Mirim*

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**Abstract:**

In 2000, the Shuttle Radar Topography Mission (SRTM) supplied for the first time a digital elevation model (DEM) at resolution levels of one and three arcseconds, using single-pass synthetic aperture radar (SAR) interferometry. Between 2013 and 2014, a kinematic positioning based on the Global Navigation Satellite System (GNSS) was carried out in the southern of Rio Grande de Sul (Brazil) and western of Uruguay, in the region of the Mirim Lagoon Hydrographic Basin, a cross-border basin with 58,407.78km$^2$, resulting in the the collect of 275,916 points with tridimensional coordinates. The objective of this work is to present the methodology and the results of the analyses performed for the validation of the vertical acuracy of the Digital Model of Elevation SRTM (DEM SRTM) through kinematic positioning based on the Global Navigation Satellite System (GNSS) in the region of the Mirim Lagoon Hidrographic Basin. The data of the GNSS kinematic surveying was post-processed with the method Positioning by PPP (Precise Point Positioning) and the elipsoidal height was converted into orthometric height through the software INTPT geoid. Considering that this study involves two countries, there has been the necessity of the use of a global model to the altitude conversion, the EGM96. The results demonstrated that the mean vertical absolute errors of the data set of altitude of the DEM SRTM vary from 0.07 m to ± 9.9 m, with average of -0.28 m and the correlation between the DEM SRTM and the GNSS surveying was 0,9995281 which is better than the standard precision value indicated in its technical specification, which is 16m, and validated the DEM SRTM for applications in morphometric and hypsometric analyses, fluvial morphology and geological studies in the Mirim Lagoon Basin.

**Keywords:** Validation; SRTM; GNSS; DEM

**Resumo:**

Em 2000, a missão do ônibus espacial para mapeamento topográfico por radar (SRTM) forneceu pela primeira vez um modelo digital de elevação (MDE) com níveis de resolução de um a três arcos de segundo, usando a técnica de interferometria por radar de abertura sintética (InSAR). Em 2013 e 2014, um levantamento cinemático baseado em Sistemas Globais de Navegação por Satélite (GNSS) foi realizado no sul do Rio Grande de Sul (Brasil) e oeste do Uruguai, na região da Bacia Hidrográfica da Lagoa Mirim, uma bacia transfronteiriça com 58407,78Km$^2$ de área, durante o qual foram coletados 275916 pontos com coordenadas tridimensionais. O objetivo deste trabalho é apresentar a metodologia e os resultados das análises realizadas para validação da acurácia vertical do Modelo Digital de Elevação SRTM (MDE SRTM) através de levantamento cinemático GNSS na região da Bacia Hidrográfica da Lagoa Mirim. O conjunto de dados do levantamento cinemático GNSS foi pós-processado com o método PPP (Posicionamento por ponto preciso) e a altitude elipsoidal foi convertida para altitude ortométrica através do programa INTPT geoid. Como o estudo envolve dois países, houve a necessidade do uso de um modelo global para a conversão da altitude, o EGM96. Os resultados demonstram que os erros verticais médios absolutos do conjunto de dados de altitude do MDE SRTM variam de 0,07m a ± 9,9m, com média igual a -0,28m e a correlação entre o MDE SRTM e o levantamento GNSS foi de 0,9995281, o que é melhor que o valor da precisão padrão indicada em sua especificação técnica, que é 16m, e valida o MDE SRTM para aplicações em análises morfométricas e hipsométricas, geomorfologia fluvial e estudos geológicos na área da Bacia Hidrográfica da Lagoa Mirim.

**Palavras-chave: Validação; SRTM; GNSS; DEM**

# 1. Introduction

The mission Shuttle Radar Topography Mission (SRTM) (Rabus et al., 2003; Van Zyl, 2001) was a joint venture between the National Aeronautics and Space Administration (NASA), the National Geospatial-Intellingence Agency (NGA), the U.S. Department of Defense (DoD), the German spatial agency (Deustches Zentrum für Luft- und Raumfahrt - DLG) and the Italian spatial agency (Agenzia Spaziale Italiana - ASI) in February, 2000, to map the reliev with Interferometric synthetic aperture radar (InSAR). In 2000, the Shuttle Radar Topography Mission (SRTM) supplied for the first time a global digital elevation model (DEM) of high quality with resolution levels of one and three arcseconds (approximately 30 and 90 m). The horizontal datum is the World Geodetic System 1984 (WGS84) ellipsoid and the vertical datum is the Earth Gravity Model (EGM96) geoid. The SRTM (C-band) data is available in various versions (V1, V2, V3 and V4). For the generation of the DEM SRTM of the Mirim Lagoon Hydrographic Basin were used SRTM images version 3, band C, with spatial resolution of 1 arcsecond, approximately 30m. These relief information have been processed and distributed by the U.S. Geological Survey – USGS (http://earthexplorer.usgs.gov/). The main objective of the SRTM project was to collect near-global topographic data with absolute horizontal and vertical accuracies better than 20 and 16m, respectively, with 90% confidence (Rabus et al. 2004; JPL, 2009).

According to Rodriguez et al. (2005), as the SRTM data were globally available, many studies have subsequently been carried out to validate the SRTM data using different types of GNSS deployed in different ways. The GNSS consists of single or dual frequency receivers deployed in the static or kinematic mode. In the static mode, a stationary receiver is deployed at the ground control points (GCPs) and its position computed. In the kinematic mode, a base receiver is fixed on a known location and the other receiver, known as the rover, can be moved over multiple unknown points with both tracking the same satellites. Post-processing involves conversion of raw data files obtained from the receivers into receiver independent format and subjecting the converted files to quality checks. They are further refined to filter errors due to atmosphere, satellite, receiver, multipath, etc. When such points are unavailable, used the kinematic deployment mode is the next best option.

One of the positioning methods GNSS is the PPP (Precise Point Positioning). According to Azambuja (2015) the PPP method has several applications as, for instance, in geodinamics, with significant advantages on the processing of GNSS nets and with centimetric precision when using the static mode, and decimetric precision when the kinematic mode is used. One of the fundamental requirements of the PPP is the use of ephemeris and corrections of the satellite clocks, both with high precision. These information have been made available free of charge by the IGS and associated centers.

The object to be positioned might be immobile, characterizing the static positioning, or be in movement, characterizing the positioning by Kinematic Precise Point. In the kinematic method, the receptor collect data while it is moving, which permits estimate the coordinates and their trajectory (MONICO, 2008).

With the advancement of the GNSS (Global Navigation Satellite System) the capacity to obtain latitude, longitude and ellipsoidal height (h) was increased. However, the altitude supplied by the satellites is linked to the reference ellipsoid. What is necessary is an altitude linked to an equipotencial surface of the terrestrial gravity field, in the case in point, the orthometric altitude (H). These two altitudes are related by geoidal ondulations (N). For obtention of orthometric altitude, based on the ellipsoidal altitude, it is necessary to know the geoidal ondulation. One of the approaches to obtain geoidal ondulation is through a geopontential model such as the EGM96 (Earth Gravity Model). The EGM96 model is used to compute geoid undulations accurate to better than one meter with reference to WGS84 ellipsoid. In Brazil, the present geoidal model is the MAPGEO2015. The figure 1 shows 30'x30' value of the geoidal undulations from EGM96.

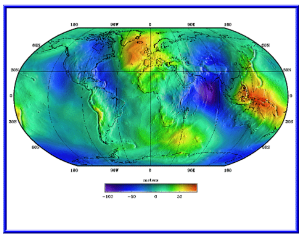

**Figure 1:** *30'x30' value of the geoidal undulations from EGM96 (CDDIS/NASA, 2004).*

Several studies deal with the validation of Digital Elevation Models (DEMs). Purinton & Bookhagen (2017) presented a validation of DEMs and comparison of geomorphic metrics on the southern Central Andean Plateau. Mukul et al. (2015) analized the accuracy of the altitude obtained through SRTM using international global navigation satellite system service (IGS) network. Karwel & Ewiak (2008) carried out an stimative of the accuracy of the SRTM terrain model on the area of Poland. Kolecka & Kozak (2013) assessed the accuracy of SRTM C- and X-Band High Mountain Elevation Data of the Polish Tatra Mountains. Agrawal et al. (2006) validated the SRTM DEM with differential GPS measurements for different terrains. Mouratidis et al. (2010) studied the RTM 3″ DEM (versions 1, 2, 3, 4) validation by means of extensive kinematic GPS measurements in the North of Greece. Gorokhovich e Voustianiouk (2006) realizaram a accuracy assessment of the processed SRTM-based elevation data by CGIAR using field data from USA and Thailand and its relation to the terrain characteristics. Van Niel et al. (2008) studied the impact of the misregistration (register error) on SRTM and DEM image differences. Becek (2008) carried out an investigation of elevation bias of the SRTM C-and X-band DEMs. Ludwig & Schneider (2006) made a validation of DEMs from SRTM X-SAR for applications in hydrologic modeling. Marschalk et al. (2004) compared DEMs derived from SRTM / X-and C-band. Rexer & Hirt (2014) compared free high resolution digital elevation data sets (ASTER GDEM2, SRTM v2.1/v4.1) and validation against accurate heights from the Australian National Gravity Database. Rodriguez et al. (2006) performed a global assessment of the SRTM performance. Smith & Sandwell (2003) studied the accuracy and resolution of SRTM data. Sun et al. (2003) validated surface highs from shuttle radar topography mission 25 using shuttle laser altimeter. E Tachikawa et al. (2011) presented a summary of validation results of the ASTER global digital elevation model version 2.

The problem dealt in this work is how to validate the DEM SRTM of the Mirim Lagoon Hydrographic Basin using control points with coordinated obatined by GNSS survey. This work is part of a research project whose objective is the automatic determination of knickpoints and the assessment of both morphometric and hypsometric parameters of the Mirim Lagoon Hydrographic Basin, employing data obtained through GNSS survey, SRTM images and geoprocessing techniques. The part described in this article presents the methodology and the results of the analyses carried out for the validation of the vertical accuracy of the DEM SRTM.

## 2. LOCATION OF THE STUDY AREA

The area chosen for the development of this study is the Mirim Lagoon Hydrographic Basin, located in the Atlantic coast of the South America, between 31°S and 34°30’S, and 52°W and 55°30’W. This basin is characterized as cross-border because it covers an area of 58,407.78km$^2$, being 47% of this area in Brazil and 53% in Uruguay. In the Brazilian territory it bathes 20 municipalities and in the Uruguayan, 5 departments. The figure 2 shows the location of the Mirim Lagoon Hydrographic Basin.

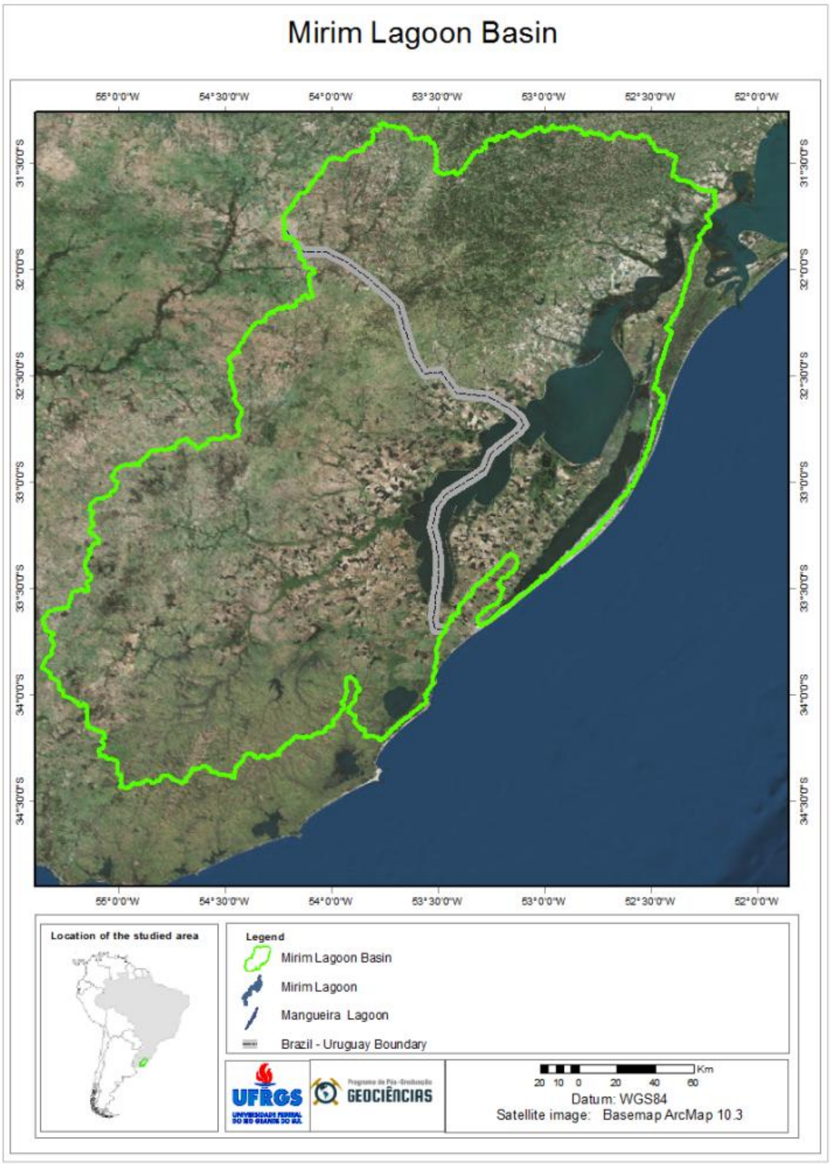


**Figure 2:** Location of the study area – Mirim Lagoon Basin.

# 3. METHODOLOGY

The methodology proposed for validation of the DEM SRTM int the Mirim Lagoon Hydrographic Basin involves the phased of data acquisition, GNSS, post-processing of data, transformation of the geometric altitudes in orthometric ones, generation of the DEM SRTM, extraction of the respective points in the DEM SRTM and the statistic analyses for validation of the model. The data used in this study are the SRTM images that cover the Mirim Lagoon Hydrographic Basin and the three dimension coordinates of the survey points with the use of double frequency GNSS receptors. The figure 3 shows a flow chart with the phases of development of the work.

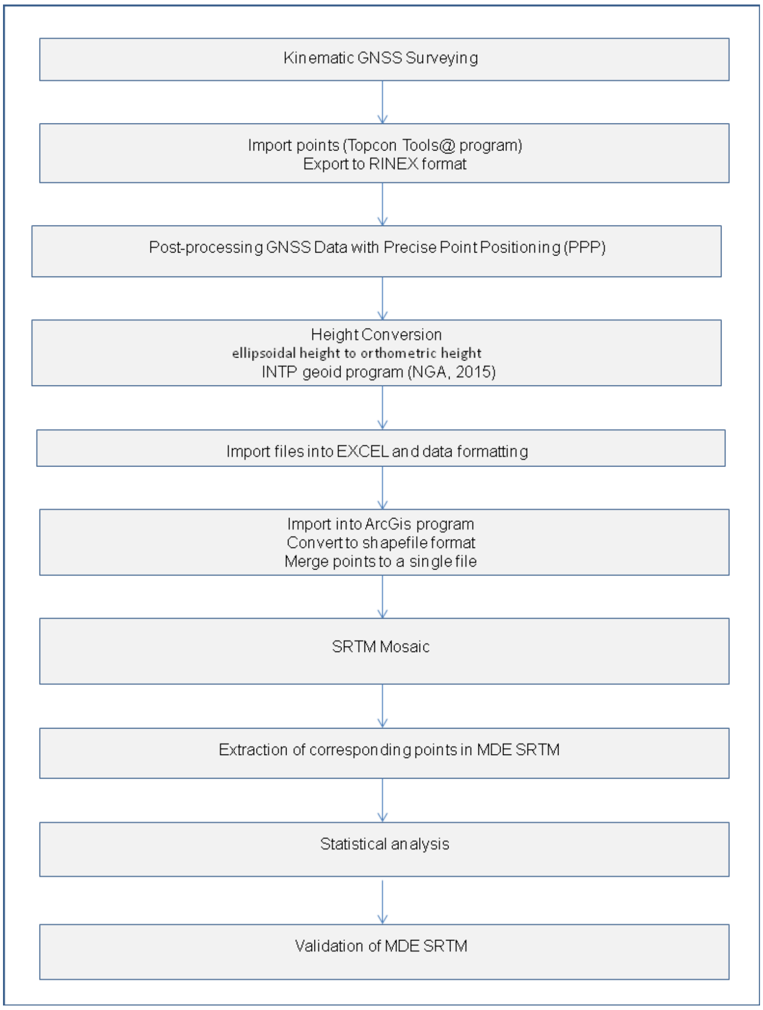


**Figure 3:** Flowchart for methodology of the SRTM validation with GNSS Kinematic Surveying.

## 3.1 Acquisition and processing of the GNSS data

The initial part of the work involved the acquisition of the three dimension coordinates of the control points (ground control points GCP´s). Because of the area's size (58,407.78km2), the post-processed kinematic relative positioning method has been adopted. The survey was carried out between 2013 and 2014, on a Kia Mohave vehicle, being the receptor fixed on the roof (figure 4). It was used a GNSS receptor of double frequency (L1/L2) of Topcon brand, model Hiper Lite+, with recording rate of 1 second.

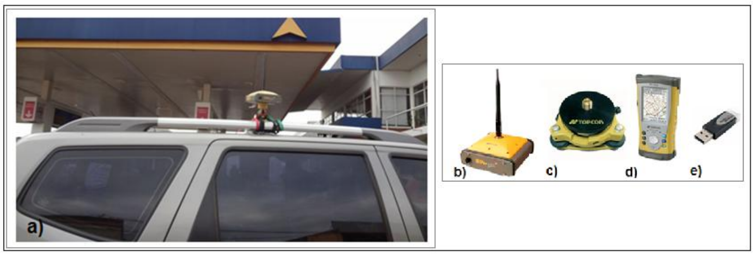


**Figure 4:** Kia Mohave vehicle (a), GNSS receptor (b) and accessories (d and e) used during the kinematic GNSS survey.

A total of 275,916 points with three dimension coordinates have been colected in the Mirim Lagoon Hydrographic Basin. The figure 5 shows the result of the kinematic GNSS survey.

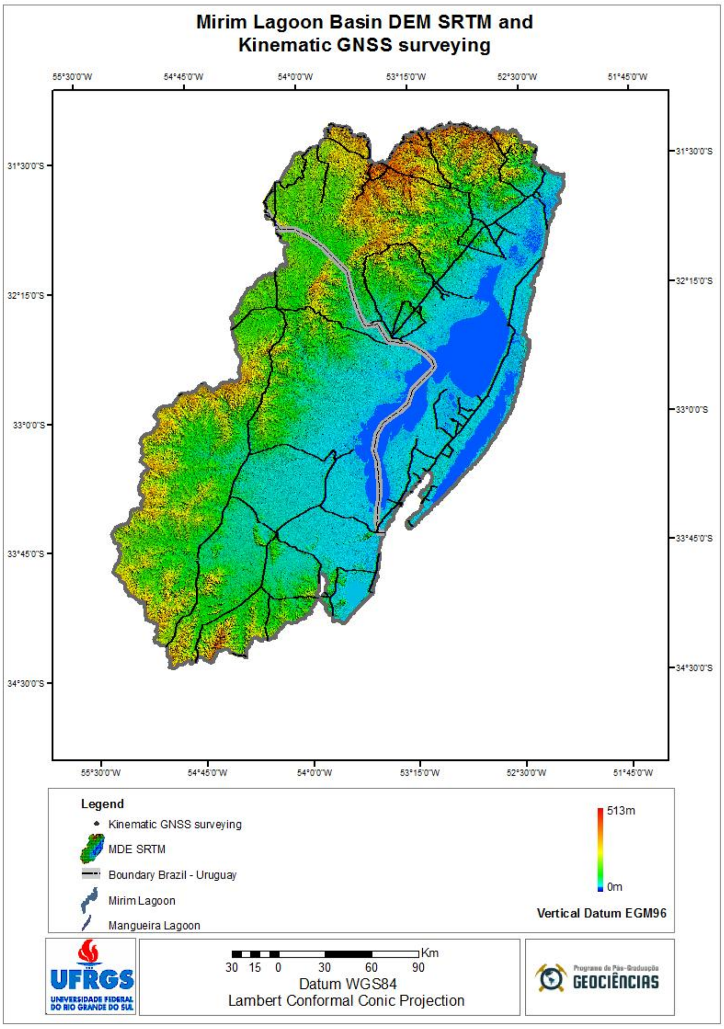


**Figure 5:** Kinematic GNSS surveying in the Mirim Lagoon Hydrographic Basin.

The files corresponding to the GNSS survey have been transfered from the receptor to the computer using a USB cable and the software Topcon Tools® version 8.2.3. The archive format of the native data of the receptor Topcon Hiper Lite+ is the TPS. After the acquisition of the files, the configuration GPS+ was chosen, which uses data from the GPS (Global Positioning System) constelation and GLONASS (Globalnaya Navigatsionnaya Sputnikovaya Sistema). The height and brand of the antenna, the reference geodesic system WGS84 and the mask of elevation of 15° were supplied. Those information are important, because the post-processing service will correct and reduce the data in the antenna phase center. The accurate antenna phase center offsets values and phase center variation factors are critical issues in GNSS precise positioning. Some GNSS users simply apply the manufacturer's recommended offset values which may not match the precise values determined by calibration process. Other users may ignore the phase center correction factors during GPS data processing. In both cases, the resulted coordinates will have errors especially the height component (Hattab, 2013; Seeber, 2003).

After this procedure, the files have been exported to the RINEX (Receiver Independent Exchange) format and post-processed individually through the Precise Point Positioning (PPP) method with the CSRS-PPP (Canadian Spatial Reference System – Precise Point Positioning). O

CSRS-PPP is a free of charge online service developed by the Geodetic Survey Division of the NRCan (Natural Resources of Canada), for the post-processing of GNSS data (NRCan, 2017), and it is available at https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php?locale=en. In Brazil, there is an analogous service for the online post-processing of GNSS data, the IBGE-PPP (Precise Point Positioning), which could not be used because the study area spreads along two countries, demanding the use of a global service.

When accessing the online service, the user chooses the survey method (either static or cinematic) and the reference system (either ITRF or NAD83). In this work it was used the kinematic positioning and the reference system ITRF (International Terrestrial Reference Frame) por ser compatível com o sistema geodésico de referência WGS84. The North American Datum of 1983 (NAD83) is used everywhere in North America except Mexico (Sickle, 2017). The four files resulting of the post-processing are sent to the user by e-mail and have the following information: one file (csv) with the corrected base station position for each time stamp during the survey; one file (pdf) with a processing relatory; one file (pos) with the stimated parameters for each observed period, the estimated coordinates and the respective standard deviation; and a file (sum) with the complete description of the processing.

## 3.2 Conversion of the ellipsoidal height into orthometric height.

The altitudes given by the GNSS receptors are geometric altitudes (elipsoidal). The determination of the orthometric altitude can be done using classic leveling techniques or the association of data obtained with GNSS receptors and geoid models. The geoid models are gravitational models of the Earth and can be global (e.g. the Earth Gravitational Model 96 - EGM96), regional (e.g. the Brazilian model MAPGEO 2015) or local, determinate for states or municipalities. In this work, it was used the global model EGM96 (Earth Gravity Model), since the study are spreads along two countries.

The geoid undulation information was computed using the INTPT geoid calculator (NGA, 2015) after adding the file with GNSS points coordinates (latitude and longitude). This geoid height calculator is an online tool that calculates the geoid undulation correction at a specified location on Earth using EGM96 gravity models. The error for EGM96 geoidal undulation is in the range ±0.5 to ±1.0 m (Lemoine et al., 1998). With the geoid undulation of each point, the following relationship was used to transform elevation from ellipsoidal height to orthometric height (Bomford, 1980):

$$H = h - N \tag{1}$$

where;
H = orthometric height;
h = ellipsoid height;
N = geoid undulation.

## 3.3 Creation of the Digital Elevation Model SRTM (DEM SRTM)

For the creation of the DEM SRTM of the Mirim Lagoon Hydrographic Basin were used 15 images SRTM, version 3, band C, with spatial resolution of 1 arcsecond (aproximatelly 30 m).

These information of the relief were processed and distributed by the U.S. Geological Survey – USGS (http://earthexplorer.usgs.gov/).
The images were processed individually for obtention of the Digital Elevation Model Hydrologically Consistent (DEMHC) and the treatment of inconsistencies. Afterwards, a mosaic with the 15 images of the basin region was created. These procedures have been executed in the software ArcGis, version 10.2.2. The figure 6 shows a representation of the DEM SRTM of the Mirim Lagoon Hydrographic Basin.

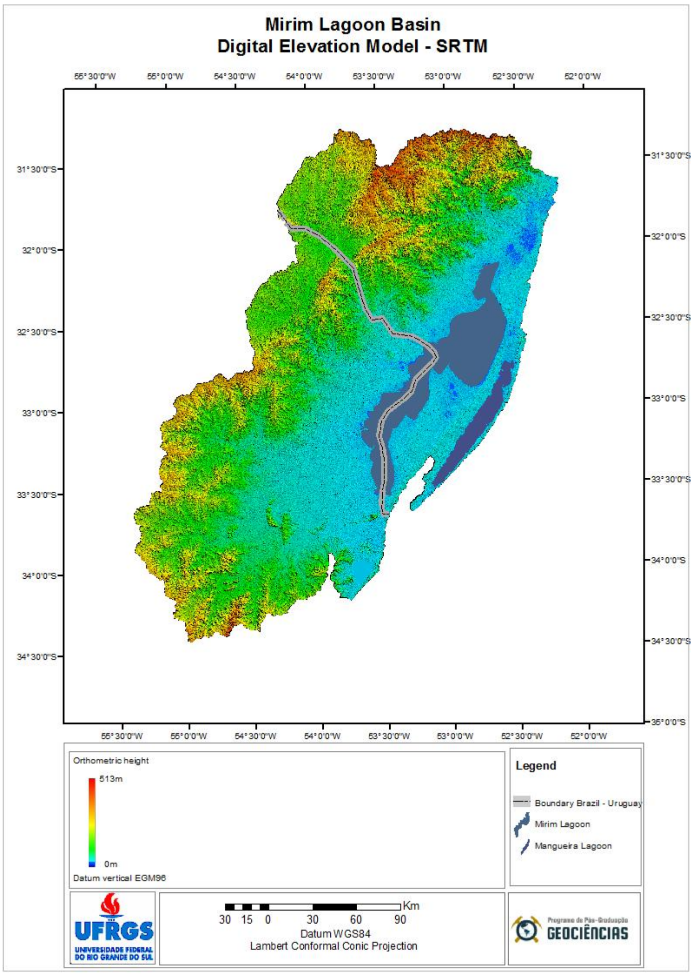


**Figure 6:** Elevation Model SRTM of Mirim Lagoon Basin.

## 3.4 Integration of the GNSS survey data with the Elevation Digital Model SRTM

After the post-processing of the GNSS survey data and the conversion of the ellipsoid heights in orthometric heights, the data were imported to the software ArcGis, version 10.2.2. For the vertical accuracy analysis and, consequently, validation of the DEM SRTM,it is necessary to compare the model with altimetric data of higher precision. In this work, the comparison was carried out with the data provided by the GNSS survey.

Extracting the DEM SRTM heights requires overlaying the GNSS points on them, and then the height value from the two data, at their position of coincidence, gives the DEM orthometric heights for computing the accuracy statistic. The extraction of the homologous points (corresponding points) of the GNSS geodesic survey of the DEM SRTM was obtained through the Extract Values to Point tool, of the software ArcGis ArcToolBox.

After the obtention of the homologous points in the DEM SRTM to the points of the GNSS survey, the differences between the orthometric altitude of each point of the GNSS survey and the DEM SRTM were determined. These differences were used in the statistic analyses.

## 3.5 Statistic analysis

In application, vertical accuracy is computed by vertical Root-Mean-Square-Error (RMSE). This mathematical relation has been widely adopted since the late 1970s. It measures the difference between the values of the DEM elevations and the values of referenced GPS elevations (Congalton, 2009).
This individual point differences are also called residuals, and the RMSE serves to aggregate them into a single measure of predictive power:

where

$$RMSE = \sqrt{\sum_i^n (e_i)^2 / n} \quad (2)$$

and

$$e_i = e_{ri} - e_{mi} \quad (3)$$

$e_{ri}$= The reference GNSS elevation at the $i_{th}$ point

$e_{mi}$= The DEM SRTM elevation at the $i_{th}$ point

n= The number of points.

The statistic analysis was performed in the software ArcGis 10.2.2, throught the extension Geostatiscal Analyst, and in the software Statistica version 12. It was examined the magnitude of absolute errors in the SRTM data. These errors were named discrepancies between the SRTM elevation and the GNSS survey points. They were used as reference and considered accurate the GNSS data of the Field survey, after the post-treating and the convertion of the ellipsoid altitudes into orthometric altitudes. The main objective of the statistic analysis was to verify if the asolute vertical precision of the DEM data excede 16 m, according to the precision specifications of the DEM SRTM.

# 4. RESULTS

The 275,916 control points collected with three dimensional coordinates in the Mirim Lagoon Hydrographic Basin have been post-processed with the method of PPP (Precise Point Positioning). The resulting files of the post processing have the information of the corrected base station position for each time stamp during the survey (csv), the shortened report of the processing (pdf), the estimated parameters for each period observed, the estimated coordinates at each moment and the respective standard deviation (pos), and the complete report of the processing (sum). The table 1 presents a part of the three-dimension coordinates, with the respective standard deviation, of the file with pos extension generated during the post-processing phase.

**Table 1:** Example of three-dimension coordinates and standard deviation obtained in the Mirim Lagoon Hydrographic Basin

| Lat (° ' " ) | Long (° ' " ) | Hgt(m) | SLat(m) | SLong(m) | SHgt(m) |
|---|---|---|---|---|---|
| -32 35 54.62967 | -53 24 56.42174 | -34.873 | 2.069 | 3.613 | 0.00357 |
| -32 35 54.62712 | -53 24 56.4133 | -35.017 | 2.031 | 3.533 | 0.00371 |
| -32 35 54.62692 | -53 24 56.41474 | -35.030 | 2.035 | 3.535 | 0.00242 |
| -32 35 54.62734 | -53 24 56.41289 | -34.917 | 2.036 | 3.536 | 0.00301 |

The table 2 presents the average and the standard deviation of the set of three-dimension points (275,916 points) post-processed by the PPP method.

**Table 2:** Mean and standard deviation of the 3D coordinates obtained in the GNSS survey.

| | SLat(m) | SLong(m) | SHgt(m) |
|---|---|---|---|
| **Mean** | 2.069 | 3.613 | 0.00357 |
| **S.D.** | 2.031 | 3.533 | 0.00371 |

The statistic analysis of the data was carried out in the sofwares ArcGis version 10.2.2, using a extension Geostatistical Analyst and in the software Statistica version 12. Initially, it was created two samples with 4000 ande 500 points, of the data from the GNSS surveying and DEM SRTM. Those samples were generated according to the processing capacity of each tool of the software used. Whenever possible, it was used all the points and when the software tool did not allowed that, it was used one of the samples. The figure 7 represents the DEM SRTM of the Mirim Lagoon and the GNSS survey points, with all survey data (N=275,916 points) and two samples (N=4000 and N=500 points).

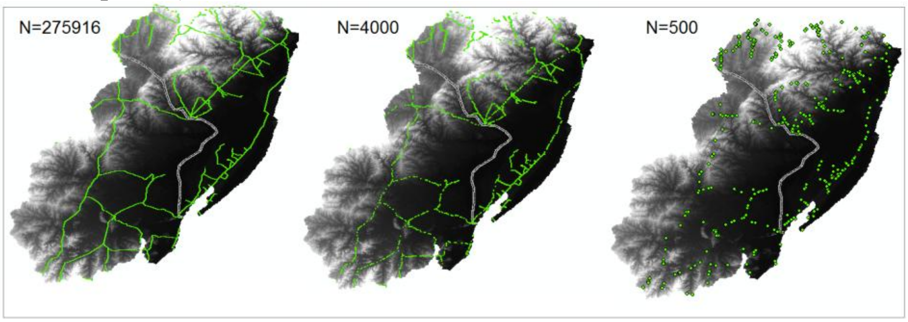


Figure 7: DEM SRTM of the Mirim Lagoon Basin and GNSS surveying with different sizes of data samples.

In the figure 8 are presented the orthometric heights resulting fromthe GNSS surveying and the orthometric heights of the DEM SRTM, for the samples N=275,916, n=4000 and N=500 points.

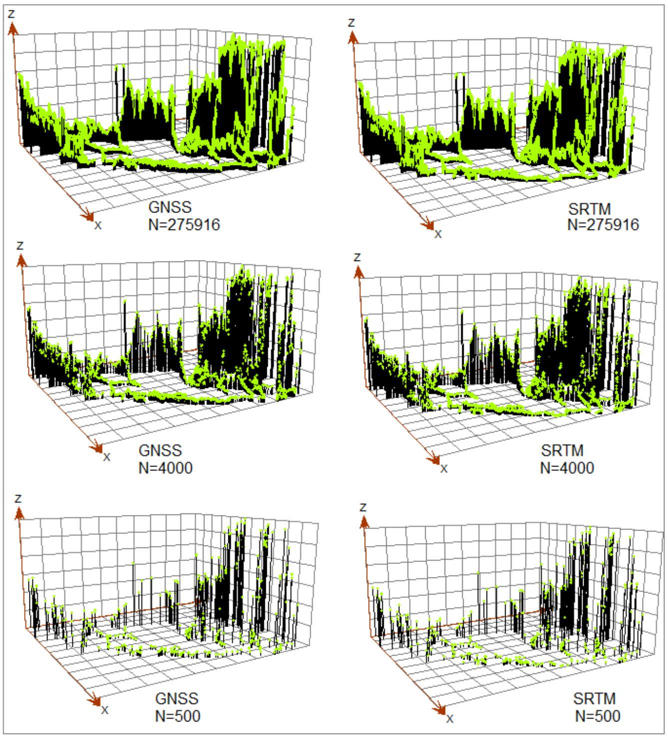


**Figure 8**: DEM Orthometric height of the GNSS surveying versus orthometric height in the DEM SRTM, for the samples: N=275,916 points, N=4000 points and N=500 points.

In the software ArcGis the analysis was carried out using all the data available (N=275,916 points). The figure 9 presents a graphic with the differences distribution between the orthometric heights DEM SRTM and GNSS surveying. The number of points in the samples is 275,916. The results demonstrate that the differences of altitude have a minimum value of -9.9998 and maximum of 9.9994. The minimum value of the differences in a module is 0,000185. The average difference between the values is -0.2817. The values of the first and third quarters are -2.9549 and 2.3028 respectively. The median is -0,33377. It is observed that the graphic presents symmetric distribution pattern. The asymmetry statistics (Skewness=0.0066466) that assess the asymmetry level in the observations is close to zero, which confirms the symmetry of the data. The short values is higher than zero which means that the distribution in study is more concentrated than the normal distribution.

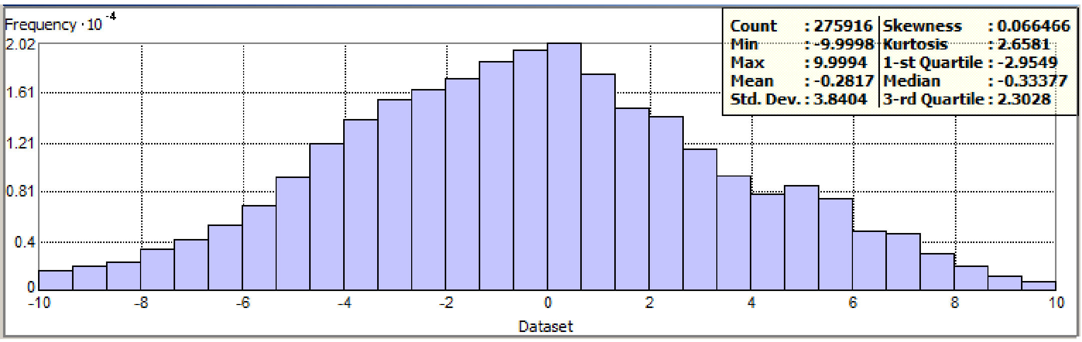


**Figure 9**: Graphic demonstrating the distribution of differences between the orthometric heights of the DEM SRTM and the GNSS surveying.

The figure 10 presents the Normal QQ Plot showing the distribuition das diferenças entre as altitudes ortométricas (orthometric heights) do DEM SRTM e do levantamento GNSS with respect to the normal distribuition. The frequency distribution of altitudes is compared to the normal distribuition.  The straight line represents the normal distribuition. The sample points follow the normal distribution.

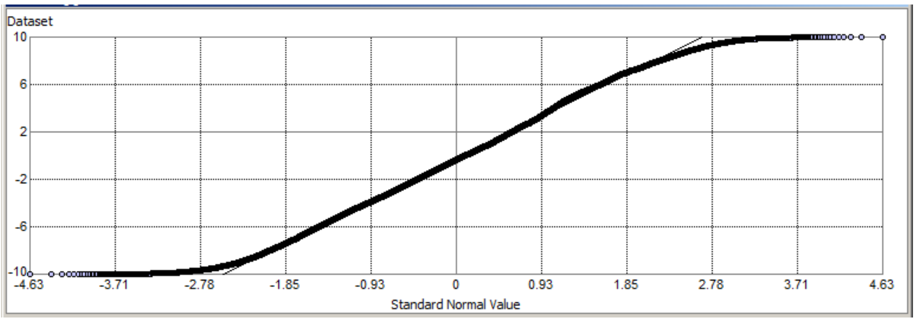


**Figure 10**: Normal QQ Plot showing the distribuition of the orthometric heights of the DEM SRTM and the GNSS surveying with respect to the normal distribuition.

The figure 11 shows a Voronoi Polygons representation of the spatial distribution of the differences between the orthometric heighs of DEM SRTM  and the GNSS surveying.

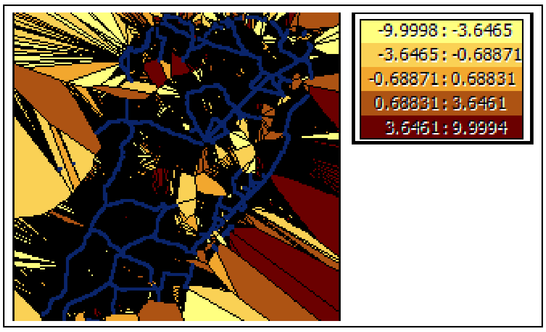


**Figure 11**: Voronoi Map of the differences between the orthometric heighs of DEM SRTM and the GNSS surveying.

The figure 12 shows a semivariogram point cloud, a covariance cloud and the differences between the orthometric heights of DEM SRTM and the GNSS surveying.

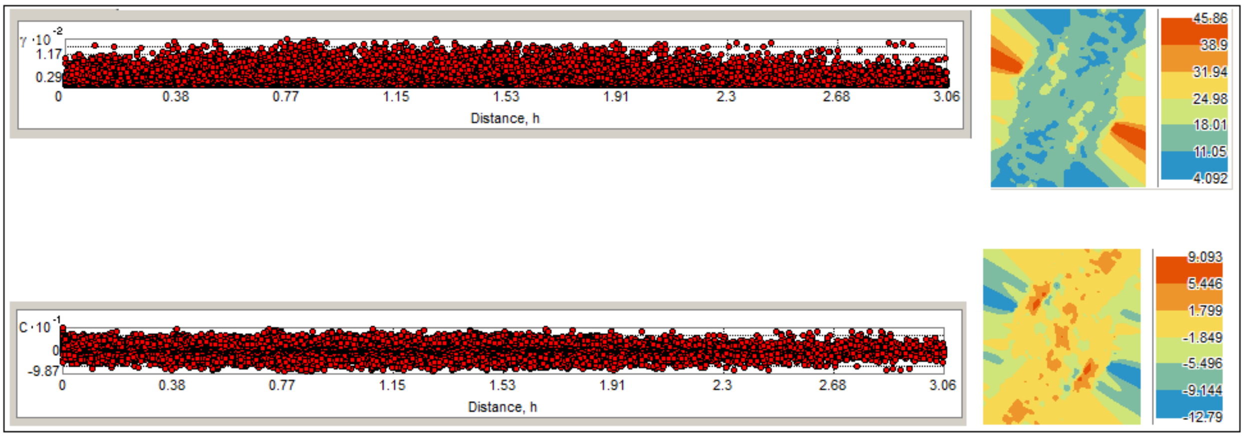


**Figure 12**: Semivariogram point cloud and difference betwen the orthometric heights of DEM SRTM and the GNSS surveying.

The figure 13 presents a two-dimensional scatterplots, showing a correlation between the GNSS surveying and the DEM SRTM, with correlation coefficient of 0.999528, indicating that the data are highly correlated.

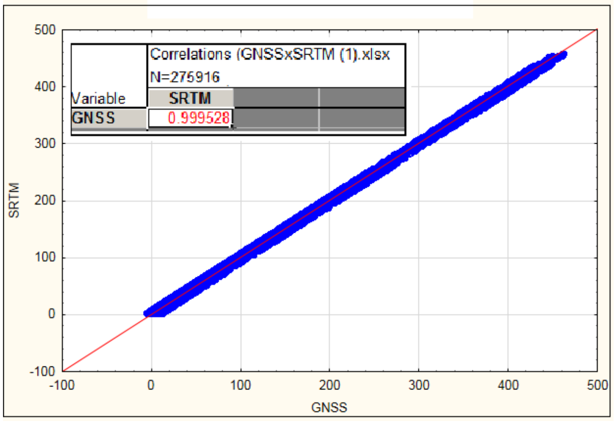


**Figure 13**: Two-dimensional scatterplots showing the correlation between the GNSS surveying and the DEM SRTM.

The figure 14 shows a comparison of results of thstatistic analysis performed in the software Statistica, for 4000 points versus the statistic analysis in the software ArcGis for 275,916 points.

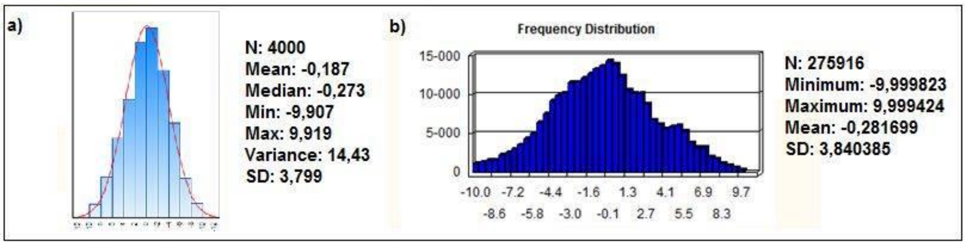


**Figure 14**: Statistics in the software Statistica (N=4000) versus software ArcGis (N=275,916).

The statistical computation for the absolute vertical accuracy of SRTM elevation data gave the values of ± 0,7m to ±9,9m, respectively and correlation between DEM SRTM and GNSS data equal to 0,9995281. For the study area, the 30 m SRTM elevation data featured a much greater absolute vertical accuracy than the absolute vertical accuracy value of ±16 m published in the SRTM data specification.

# 5. CONCLUSIONS

The present article presented the methodology adopted and the results of the analyses for validation of vertical of the accuracy of Digital Elevation Model SRTM (DEM SRTM) through the kinematic positioning based on the Global Navigation Satellite System (GNSS) in the region of Mirim Lagoon Hydrographic Basin. The objective proposed were reached using the methodologies for acquisition of GNSS data, the post-processing of these data, the transformation of the geometric height in orthometric heights, the generation of DEM SRTM, the extraction of the corresponding points in the DEM SRTM and the statistic analyses for results validation.

The post-processed kinematic relative method of positioning was suitable for acquisition of three-demension coordinates of the control points in the Mirim Lagoon Hydrographic Basin, corresponding to 58,407.78km$^2$, for the validation of the DEM SRTM. The total number of points surveyed for the model validation was 275,916. The results showed that the height differences have a minimum value of -9.9998 and maximum of 9.9994. The minimum value of differences in module is 0.000185. The average difference of the values is -0.2817. The values of the first and third quarters are -2.9549 and 2.3028 respectively. The median is -0.33377. The asymmetry statistic (Skewness=0.0066466) is close to zero, confirming the symmetry of the data, with a distribution more concentrated than the normal one. The correlation coefficient 0.999528 between the GNSS surveyng and the DEM SRTM, demonstrate that the data are highly correlated.

The statistic analysis assessed the errors magnitude in the SRTM data, compared to post processes GNSS data, and the ellipsoidal heights converted into orthometric heights. Considering that the main objective of the statistics analysis was to verify if the absolute vertical precision of the DEM data exceed the values 16 m, according to the precision specifications of DEM SRTM, the statistical computation for the absolute vertical accuracy of SRTM elevation data gave the values of ± 0,7m to ±9,9m, respectively and correlation between DEM SRTM and GNSS data equal to 0,9995281. For the study area, the 30 m SRTM elevation data featured a much greater absolute vertical accuracy than the absolute vertical accuracy value of ±16 m published in the SRTM data specification. Therefore, the results demonstrate that the methodology is suitable for the validation of the DEM SRTM of the Mirim Lagoon Hydrographic Basin.

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# 3 ARTIGO SUBMETIDO À REVISTA THE INTERNATIONAL JOURNAL OF RIVER BASIN MANAGEMENT

## MORPHOMETRIC AND HYPSOMETRIC ANALYSIS OF THE MIRIM LAGOON HYDROGRAPHIC BASIN, TRANSBOUNDARY WATER RESOURCES REGION.

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MORPHOMETRIC AND HYPSOMETRIC ANALYSIS OF THE MIRIM LAGOON HYDROGRAPHIC BASIN, TRANSBOUNDARY WATER RESOURCES REGION

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ABSTRACT

The morphometric and hypsometric characterization of river basins allows a better understanding of its performance as a system, promotes the correlation with its characteristics, and strengthens many studies. The use of quantitative and qualitative methods to characterize a river basin allows a greater understanding of its dynamics, therefore the use of many parameters is very important. This article presents the morphometric and hypsometric analysis of the Mirim Lagoon basin, a transboundary basin located on the Atlantic coast of South America, between parallels 31°S and 34°30'S and meridians 52°W and 55°30'W, with an area of 58,407.78 km$^2$, with 47% in Brazilian territory and 53% in Uruguayan territory. The analysis and acquisition of the parameters was done with geoprocessing techniques, in the software ArcGIS, version 10.2.2, using spatial analysis and data manipulation tools. Shuttle Radar Topographic Mission (SRTM) information was used for the morphometric and hypsometric analysis of the study area. For the Mirim Lagoon Basin area coverage, 15 SRTM images were required. The results show that the use of SRTM data in GIS allows the characterization of the watersheds, which is useful in the management of water resources and environmental studies, proving to be a practical and viable alternative to minimize costs and time in the work execution.

**Keywords:** SRTM; Morphometric Analysis; Hypsometric Analysis; Fluvial Geomorphology; GIS

## 1. INTRODUCTION

The analysis of watersheds began to be more objective after 1945, with the publication by Horton (1945) who tried to establish the development laws of rivers and their basins and quantitatively approached the drainage basins. His study served as basis to the methodological concept and originated many researches by several followers (Christofoletti, 1980). Morphometry is the measurement and mathematical analysis of the configuration of the earth's surface, shape and dimension of its landforms (Clarke, 1966). This analysis can be achieved through the measurement of linear, aerial and relief aspects of the basin. Morphometric and hypsometric analysis provides a quantitative description of the basin geometry to understand initial slope or inequalities in the rock hardness, structural controls, recent diastrophism, geological and geomorphic history of drainage basin (Strahler,1964). The drainage basin is a basic unit in the morphometric investigation because all hydrological and geomorphic processes occur within the watershed, where denudation and gradation processes are clearly seen, and it is indicated by several morphometric studies (Horton, 1945; Strahler 1952, 1964; Shreve 1969; Evans 1972; Chorley 1969; Chorley et al., 1984, 1957; Merritts & Vincent 1989; Merritts et al.,1994). The description of drainage basins and channel networks, based on contributions made by Horton (1932 and 1945) and complemented by Chorley (1957), Melton (1958), Miller (1953), Schumn (1956), Strahler (1964), and others, went from a purely qualitative and deductive study to rigorous science that provides numerical values that can be applied in practice.

Several studies deal with the analysis of morphometric parameters, especially the works by Schumm (1956), Christofoletti (1969), Horton (1945), among others. Pareta (2011) analyzed the Watershed of Yamuna Basin, India with digital elevation models and Geoprocessing techniques. Rai et al. (2017) made a GIS-based approach using DEM and analyzed the Kanhar River Basin. Abboud & Nofal (2017) analyzed the morphometry of wadi Khumal basin, western coast of Saudi Arabia, using Remote Sensing and GIS techniques. Aher et al. (2014) used an approach involving Remote Sensing and GIS for the morphometric characterization quantification for management in the semi-arid tropics of India. Ahmed & Srinivasa (2016) analyzed the hypsometry of the Tuirini drainage basin; Ahmed et al. (2010) conducted a study at the Bandihole sub-watershed basin in Karnataka.

In the 1980s, the development of Remote Sensing with interferometry radars and the creation and implementation of computational tools with more user-friendly interfaces, associated with a new scientific time of the Geosciences, enabled the use of "remote" measurement techniques. These techniques contributed to the development of computational tools for the treatment of geographic information, called Geographic Information Systems (GIS). This has been consolidated by scientific studies carried out in the fields of Cartography, Geology, Geography, Geomorphology, among others, and in research carried out in the public and private sectors for planning and territorial management of their activities. Since then, Geomorphology has been marked by the use of quantitative techniques. But regardless of the conceptual and methodological reform, the general goal remains the same: to study and interpret the forms of terrain relief and the mechanisms responsible for its modeling, at all scales of analysis, from global to local scale models.

The analysis and modeling of geomorphological systems in a computational environment have optimized the data acquisition and analysis that previously required expensive and long field and office assessments, such as the case of the morphometric analysis of hydrographic basins. The morphometric analysis aims to quantify relief attributes, to classify it and to compare modeling and evolution in different climate (exogenous) and structural (endogenous) contexts (Horton, 1945; Strahler, 1954; Schumm, 1956; Strahler, 1957; Christofoletti, 1980).

One of the technologies used in the analysis of geomorphological systems is the computational processing of data obtained by remote sensing, especially the data provided by interferometric radars, such as those from SRTM (Shuttle Radar Topography Mission). These data allow the generation of a topographic model for the entire earth's surface and can serve as the basis for studies in several geomorphological analysis units (geomorphological systems), such as a water basin.

The most common technique for deriving morphological relief attributes in a digital environment is through the use of Digital Elevation Models (DEMs) and the digital hydrographic network. Computational routines are applied to these data for extraction of morphometric parameters. The DEMs and the hydrographic networks must have morphological and hydrological consistency for the results obtained in the morphometric analyses to be valid. The use of DEMs to represent the relief and to generate the drainage network has been expanded since the availability of altimetric databases obtained by remote sensing, more specifically those generated by imaging via radiometric interferometry.

Geomorphometry, defined as the science of quantitative description and analysis of landscape geometric-topological features (Pike, 1995; Pike, 2009; Bettu et al., 2013), has as one of its main objectives the development of objective and replicable classification methods for the relief shapes, providing indicators regarding the geomorphic processes acting on the relief, based on remote sensing data. The basic concept of Geomorphometry is the morphometric parameterization, usually derived from a DEM, including specific information about the shape of the Earth's surface (Wilson & Gallant, 2000; Smith et al., 2008; Bettu et al., 2013). Wilson & Gallant (2000) classify the morphometric parameters as primary (obtained directly from DEM, such as slope and curvature) and composite (calculated from primary parameters, such as the topographic index).

The hypsometry and morphology of the relief, the Geomorphometry bases, result from complex interactions between lithology, tectonics, climate and erosional processes, which makes it of paramount importance in geomorphometric studies for Earth sciences. Thus, quantitative descriptors of the relief characteristics and its structure are considered essential indices to differentiate the relief shapes and serve as the basis for quantitative research in Geomorphology.

In this context, this study is part of the research project that aims to perform the automatic determination of Knickpoints of the Mirim Lagoon Hydrographic Basin, using data obtained from GNSS surveys and SRTM images. The part described in this article presents the results of the spatial analysis performed to obtain the morphometric and hypsometric parameters, as well as for automatic hydrograph generation, from the Mirim Lagoon Hydrographic Basin, based on SRTM data.

## 2. LOCATION AND CHARACTERIZATION OF THE STUDY AREA

The study area is the Mirim Lagoon Basin, located on the Atlantic coast of South America, between parallels 31°S and 34°30’S and between meridians 52°W and 55°30’W, with an area of 58,407.78 $km^2$, with 47% in Brazilian territory and 53% in Uruguayan territory. The Brazilian side includes 20 municipalities and the Uruguayan side, 5 departments. Figure 1 shows the location of the Mirim Lagoon Basin.

The Mirim Lagoon Basin is described in the literature as a Paleogeographic unit formed by the existence of large extensional forces that produced fractures by the eruption of volcanic lava that allowed the sinking of large rock masses. These phenomena began 150 million years ago when the Gondwana continent broke and they are linked to the opening of what is now the Atlantic Ocean.

The flood area of the Mirim Lagoon is the result of Middle and Upper Jurassic sinking processes that generated the tectonic trench of this lagoon. During the Cenozoic, the continuous and moderate sinking process, combined with the slow vertical movements that occurred during the Tertiary and the Quaternary, gave rise to the lower altitudes and the higher and more extensive interfluves. The interaction of the geological development with complex paleoclimate elements, mainly during the Quaternary, resulted in the present relief, represented by the flatlands and inselbergs. The coastline is the result of marine transgressions, which gave rise to the majority of the swamps and coastal lagoons formed during the Holocene. The geological basement of the watershed is composed of a complexity of South American shield structures. The western area is characterized by a positive orogenic trend that, at the end of the Cenozoic, originated the formation of low altitude reliefs (hills and ranges), reaching a maximum elevation of 520 m. In the eastern portion of the basin, the chemical weathering processes began in the Permocarboniferous, until the Jurassic, which allowed an accumulation of sediments in the coastline. (Probides, 2000, Montaña & Bossi, 1995, Steike & Sato, 2008).

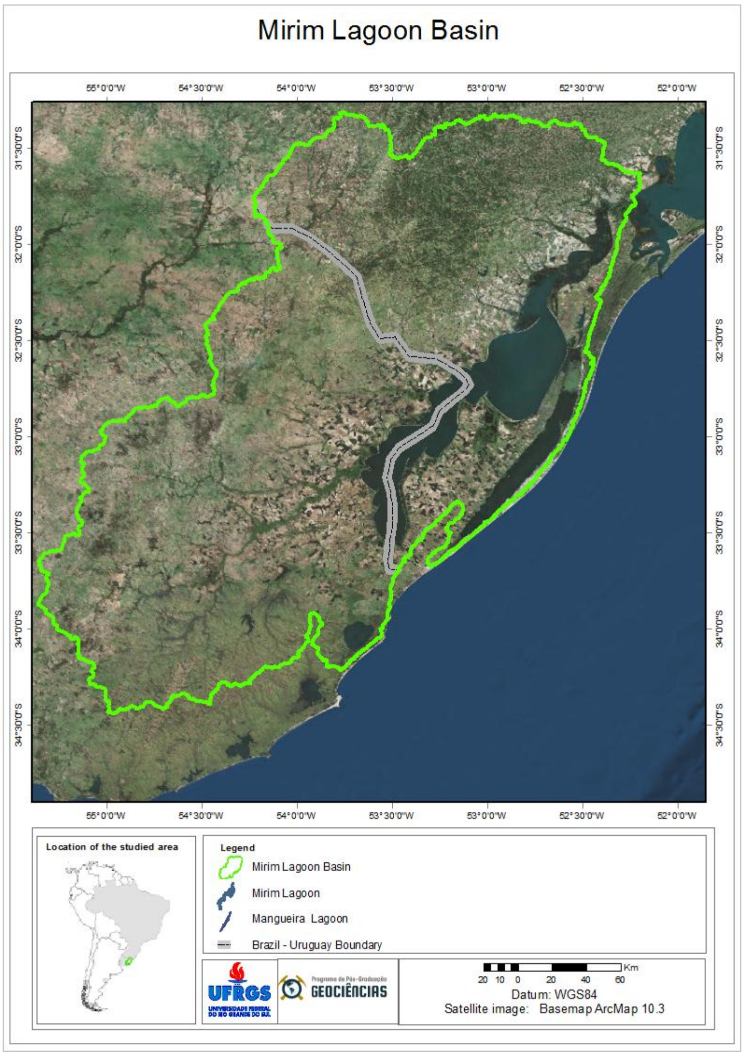


Figure 1. Location of the studied area.

# 3. METHODOLOGY

The The research problem approached in this study is how to automatically generate the hydrography and obtain the morphometric and hypsometric parameters of the Mirim Lagoon Hydrographic Basin from SRTM data. The methodology proposed for the development of the activities needed to solve the problem at hand involves the generation of the SRTM DEM, the definition of the appropriate map projection for the study area, the automatic acquisition of hydrology and the calculation of the morphometric and hypsometric parameters. The data used in this study are the SRTM images, and the analyses and acquisition of the parameters were conducted with the software ArcGIS (ESRI), version 10.2.2. Figure 2 shows a flowchart of the development stages of the work.

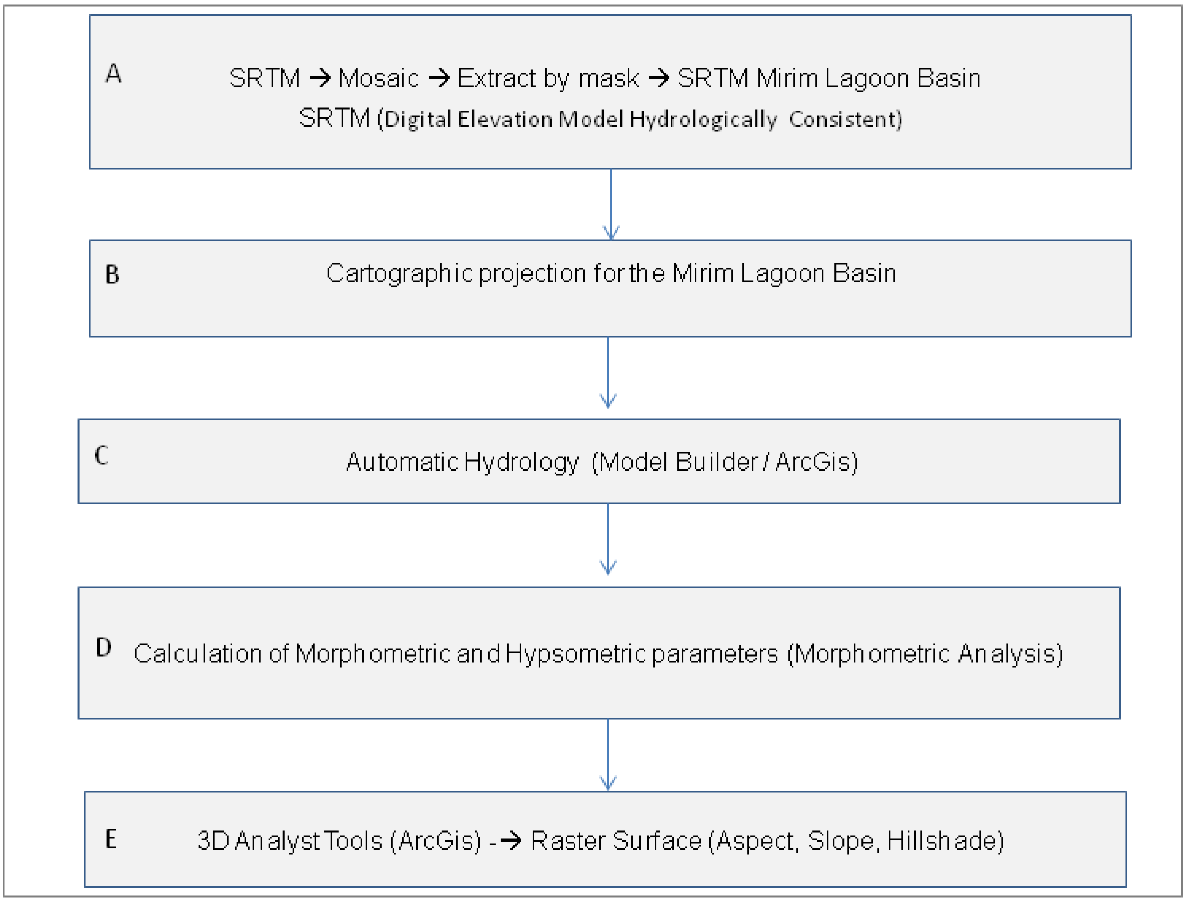


Figure 2 - Flowchart of the development stages of the work.

## 3.1 Generation of the SRTM Digital Elevation Model (SRTM DEM)

SRTM-DEMs are generally given by rectangular matrix grids in which, for each pixel, a numerical value is associated with the altitude. The rectangular grid format is most commonly used because its structure is more compatible with digital image processing tools. The computational structure of this type of grid is the same as that of digital images, differentiated by the fact that the information stored in the pixels is not associated to the visible electromagnetic radiation, but to Radar waves (active microwave frequency) corresponding to altimetric values when obtained by interferometry.

To generate the SRTM DEM of the Mirim Lagoon Basin, SRTM images were used, version 3, band C, with a spatial resolution of 1 arcsecond, approximately 30 meters. These relief data were processed and distributed by the U.S. Geological Survey - USGS (http://earthexplorer.usgs.gov/). A total of 15 images were used to cover the basin region. The list of these images is shown in table 1.

Table 1. - SRTM images covering the Mirim Lagoon Basin.

| | | |
|---|---|---|
| s32_w053_1arc_v3 | s33_w054_1arc_v3 | s34_w055_1arc_v3 |
| s32_w054_1arc_v3 | s33_w055_1arc_v3 | s34_w056_1arc_v3 |
| s32_w055_1arc_v3 | s33_w056_1arc_v3 | s35_w054_1arc_v3 |
| s32_w056_1arc_v3 | s34_w053_1arc_v3 | s35_w055_1arc_v3 |
| s33_w053_1arc_v3 | s34_w054_1arc_v3 | s35_w056_1arc_v3 |

Initially, individual image processing was performed to obtain the Hydrologically Consistent Digital Elevation Model (MDEHC), and to fill the spurious pits present in the SRTM DEM. Once the inconsistencies were dealt with, the mosaic was generated with the 15 images that cover the region of the basin. Subsequently, a mask was used, in vector format, representative of the basin contour. These procedures were done in the ArcGIS software, version 10.2.2.

Figure 3 shows the SRTM images covering the Mirim Lagoon Basin, the SRTM mosaic of the region, and the SRTM mosaic trimmed with the basin contour vector mask. Figure 4 shows the representation of the Mirim Lagoon Basin SRTM DEM.

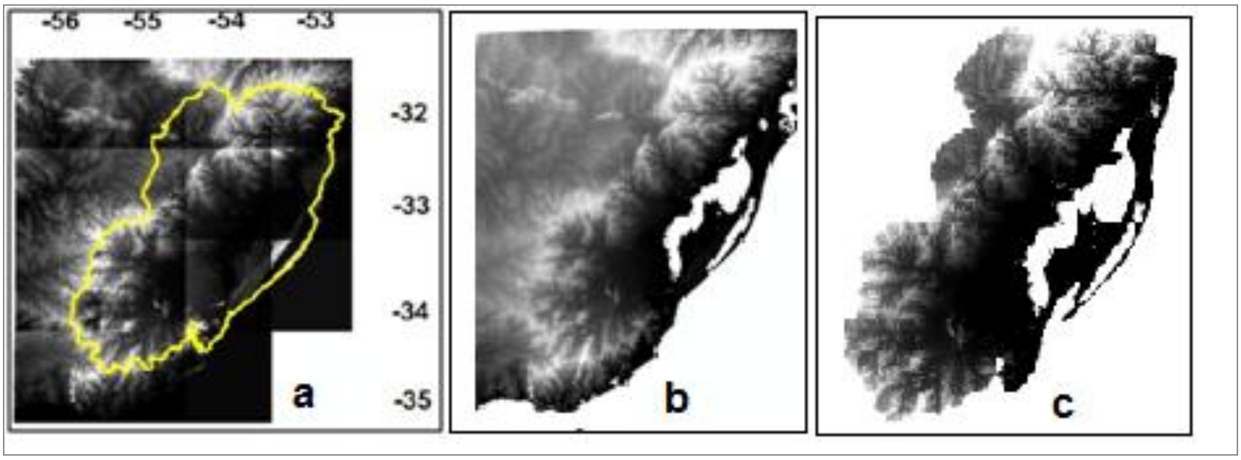


Figure 3 - SRTM coverage of the Mirim lagoon basin region (a), SRTM mosaic (b) and SRTM mosaic trimmed with the basin contour vector mask (c).

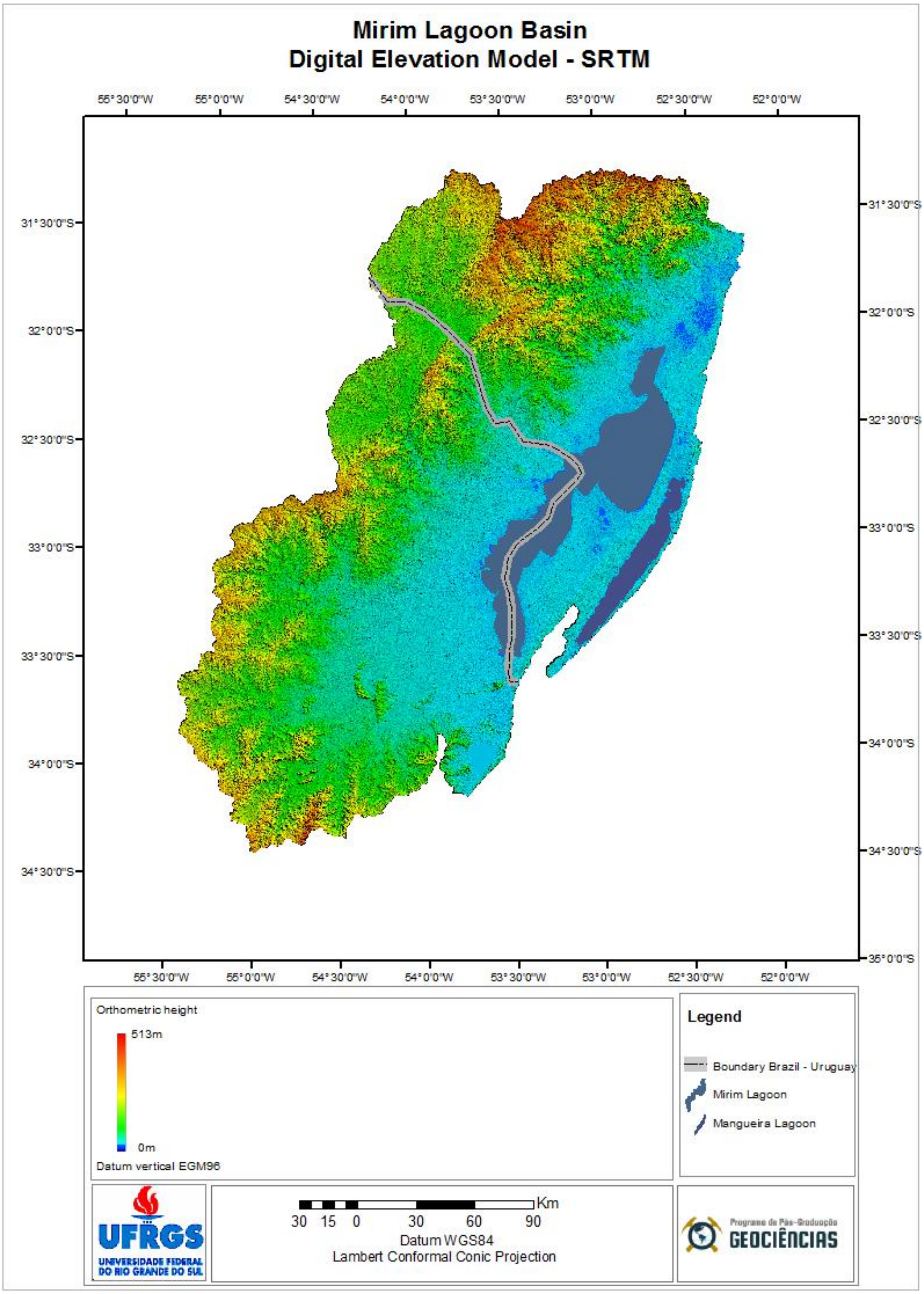


Figure 4. Digital Elevation Model SRTM of Mirim Lagoon Basin.

## 3.2 Definition of the Map Projection.

In order to minimize the distortions inherent to the representation process, and consequently to improve the quality of the obtained results, it was decided to define a specific map projection for the study area. After analyzing the characteristics of the region, the Lambert Conformal Conic Projection with Two Standard Parallels was chosen.

The standard parallels were determined using Kavrayskiy's constant (K = 5), suitable for areas with greater latitude extension (Maling, 1992). Therefore, the adopted map projection was defined by adopting the parameters shown in table 2. This projection was used in all analyses and representations.

Table 2. Map Projection Parameters.

| | |
|---|---|
| False Easting | 0.000000 |
| False Northing | 0.000000 |
| Central Meridian | 54º W Greenwich |
| Standard Parallel 1 | 34º 12’ S |
| Standard Parallel 2 | 31º 48’ S |
| Latitude of Origin | 31º S |

## 3.3 Automatic Hydrographic Data Acquisition.

The hydrography was obtained automatically based on the SRTM DEM of the Mirim Lagoon Basin. To this end, a model was developed with the Model Builder tool (ArcGIS, 10.2.2), as shown in the flowchart of figure 5.

Based on the raster format SRTM DEM, the flow directions are extracted, and the cumulative flow is calculated. After that, different thresholds were defined of the contribution area that allows the drainage network to be obtained with a greater or lesser degree of detail. Thus, any cell in the matrix of the contribution area that is higher than the threshold is considered as part of the drainage. And finally, this drainage network was transformed to a vector format (shapefile).

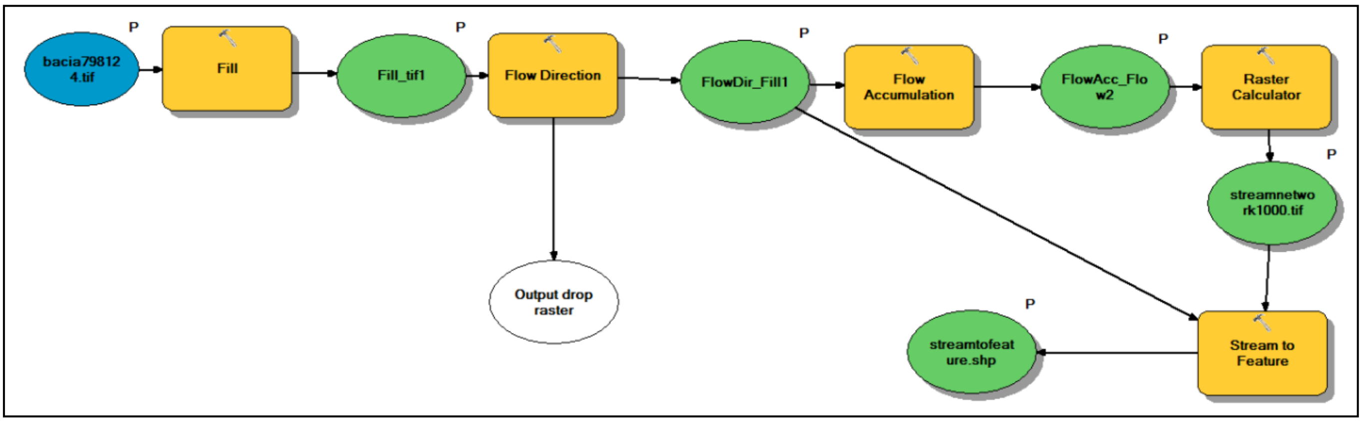


Figure 5 - Flowchart of the process of automatic hydrograph generation of the Mirim Lagoon Basin.

## 3.4 Calculation of Morphometric and Hypsometric Parameters

Morphometric and hypsometric parameters were calculated using the Morphometric Analysis tool (ESRI, 2016), developed in the Python programming language and integrated with the ArcGIS program within the ArcToolbox module. The mathematical formulas used in the script is shown in table 3.

Table 3. Formulas Used in Calculation of Morphometric Parameters. Source: modified from Beg (2015).

| **Morphometric Parameter** | **Formula** | **Author** |
|---|---|---|
| Number of stream orders (Nu) | $N_u=N_1+N_2+...+N_n$ | Horton (1945) |
| Length of stream orders (Lu)(ms) | $L_u=L_1+L_2+.....+L_n$ | Horton (1945); Strahler (1964) |
| Bifurcation Ratio (Rb) | $R_b=N_u/N_{u+1}$ | Schumm (1956); Strahler (1964) |
| Mean bifurcation ratio (Rbm) | Rbm = average of bifurcation ratio of all orders | Strahler (1957) |
| Total Basin Area (A) (Km2) | Projected Area enclosed by basin boundary | Schumm (1956) |
| Total Basin perimeter (P) (Km) | Length of horizontal projection of basin water divide | Schumm (1956) |
| Basin Length (Lb) (Km) | Distance from outlet to Farthest point on basin boundary | Schumm (1956) |
| Fitness ratio (Rf) | Rf = Lc/P | Melton (1957) |
| Form factor (Ff) | $Ff = A/Lb^2$ | Horton (1932) |
| Shape Factor (Sf) | $Sf = Lb^2/A = 1/Ff$ | Strahler (1964) |
| Relative perimeter (Rp) | Rp = A/P | Schumm (1956) |
| Length Area Relation (Lar) | $Lar = 1.4 A^{0.6}$ | Hack (1957) |
| Rotundity coefficient (Rc) | $Rc = \frac{Lb^2 \pi}{4A}$ | Strahler (1945) |
| Mean Basin Width (Wb) | $W_b = A / L_b$ | Horton (1932) |
| Drainage Texture (Dt) | $D_t= N_u/P$ | Horton (1945) |
| Compactness Coefficient (Cc) | $Cc = 0.282 P \sqrt{A}$ | Horton (1945) |
| Circularity ratio (Rc) | $Rc = \frac{4\pi A}{P^2}$ | Miller (1953) |
| Elongation ratio (Re) | $\mathrm{Re} = \frac{D_c}{L_b} = 1.29\sqrt{\frac{A}{L_b}}$ | Schumm (1956) |
| Drainage density (Dd) (km/km2) | $Dd = \sum_{i=1}^{K}\sum_{i=0}^{n} L_u / A$ | Horton (1932); Strahler (1964) |

| | | |
|---|---|---|
| Stream frequency (F) | $F = \sum_{i=1}^{K} N_u / A$ | Horton (1932) |
| Constant of channel maintenance (Ccm) ($km^2$/km) | $Cc_m = \frac{1}{Dd} = A / \sum_{i=1}^{K} \sum_{i=0}^{N} Lu$ | Schumm (1956); Strahler (1964) |
| Infiltration Number (Ifn) | $Ifn = F \; Dd$ | Faniran (1968); Pareta (2011) |
| Drainage Intensity (Di) | $Di = F / Dd$ | Faniran (1968); Pareta (2011) |
| Average Length of Overland Flow (Lg) (Km) | $Lg = 1/2 \; Dd$ | Horton (1945) |
| Total Basin Relief (H) | H = Z - z | Strahler (1952) |
| Maximum Height of basin | Select point from DEM | Beg(2015) |
| Relief Ratio | Rhl=H / Lb | Schumm (1956); Melton (1957) |
| Relative Relief Ratio | Rhp=H * 100 / P | Melton (1957) |
| Gradient Ratio | Rg = (Z - z ) / Lb | Sreedevi et al. (2005); Pareta (2011) |
| Ruggedness Number | Rn=Dd * (H /1000) | Strahler (1964) |
| Melton Ruggedness Number | MRn=H/A 0.5 | Melton (1965) |
| Terrain Undulation Index | TUi=As/A | Beg (2015) |

The steps for obtaining the morphometric and hypsometric parameters are presented in figure 6.

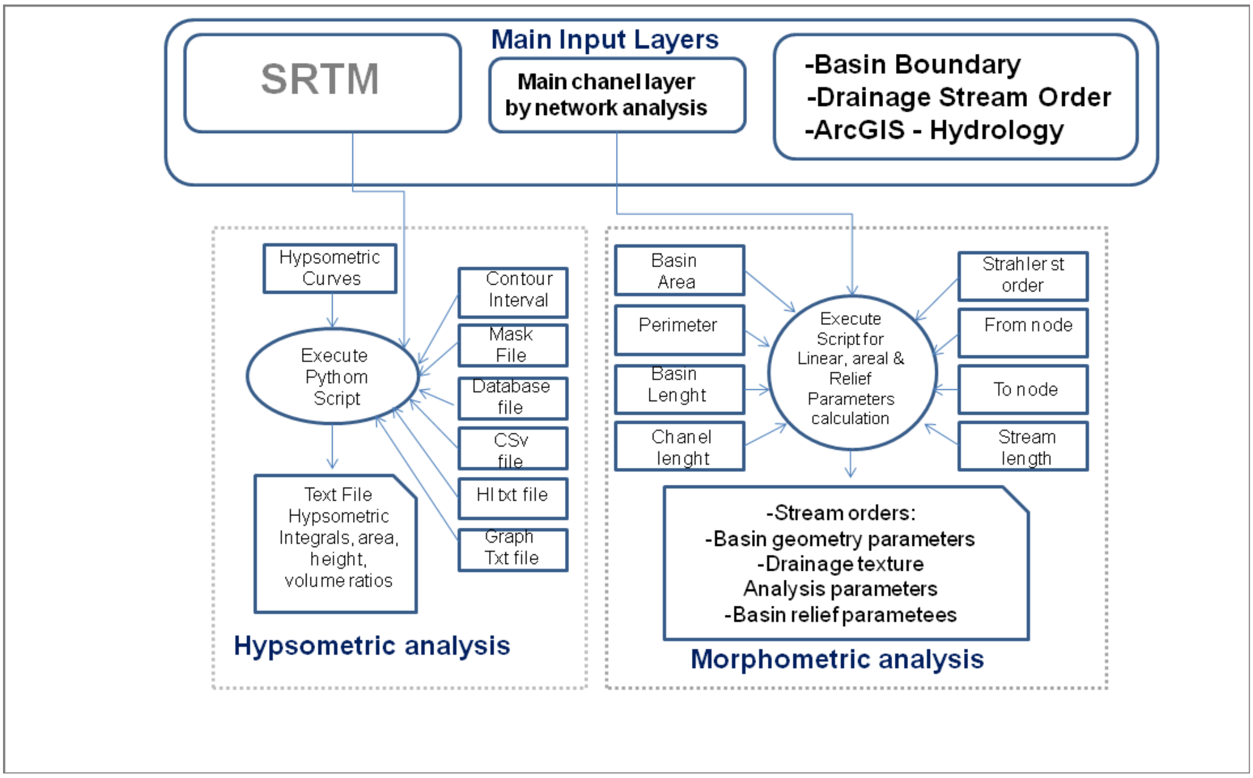


Figure 6 – Flowchart with the morphometric and hypsometric analysis steps. Source: modified from Beg (2015).

# 4. RESULTS

## 4.1 Morphometric Parameters of the Mirim Lagoon Basin

Based on spatial analysis and manipulation of the SRTM data in GIS environment, the morphometric parameters of the Mirim Lagoon Basin were calculated using computational routines. These parameters refer to drainage network, basin geometry, drainage texture analysis and basin relief.

The results of the drainage network parameter calculations are shown in table 4. In analyzing these results, it can be seen that the drainage network of the Mirim Lagoon basin is of ninth-order, according to Strahler's classification (1952), and predominantly dominated by low order channels. Of a total of 143969 channels, 112210 are first-order, 24912 are second-order, 5344 are third-order, 1167 are fourth-order, 256 are fifth-order, 62 are sixth-order, 13 are seventh-order, 4 are eight-order, and only 1 is a ninth-order channel. The river order number is important in the analysis of geological structures, especially fractures, since lower order channels are the main indication of neotectonic movement. In addition, the drainage pattern is dendritic, indicating that there is no structural or tectonic control. Additionally, the mean bifurcation ratio of 4.3 corresponds to a heavily dissected drainage basin (Strahler, 1957).

Table 4. Drainage Network Parameters

| | |
|---|---|
| Number of stream order 1 | 112210 |
| Number of stream order 2 | 24912 |
| Number of stream order 3 | 5344 |
| Number of stream order 4 | 1167 |
| Number of stream order 5 | 256 |
| Number of stream order 6 | 62 |
| Number of stream order 7 | 13 |
| Number of stream order 8 | 4 |
| Number of stream order 9 | 1 |
| Total no. of stream order | 143969 |
| Length of stream order 1 | 57375074.4728 m |
| Length of stream order 2 | 26857148.3849 m |
| Length of stream order 3 | 13602785.0494 m |

| | |
|---|---|
| Length of stream order 4 | 6457937.94345 m |
| Length of stream order 5 | 3199084.62803 m |
| Length of stream order 6 | 1459689.51841 m |
| Length of stream order 7 | 726182.851915 m |
| Length of stream order 8 | 332985.056118 m |
| Length of stream order 9 | 38278.3950477 m |
| Total length of streams | 110049166.3 m |
| Rb for 1:2 | 4.50425497752 |
| Rb for 2:3 | 4.66167664671 |
| Rb for 3:4 | 4.57926306769 |
| Rb for 4:5 | 4.55859375 |
| Rb for 5:6 | 4.12903225806 |
| Rb for 6:7 | 4.76923076923 |
| Rb for 7:8 | 3.25 |
| Rb for 8:9 | 4.0 |
| Average Bifurcation ratio | 4.30650643365 |

Figure 7 shows some results of automatic hydrography generation from the SRTM DEM processing. In order to do so, different thresholds were used to obtain drainage networks with a greater or lesser degree of detail.

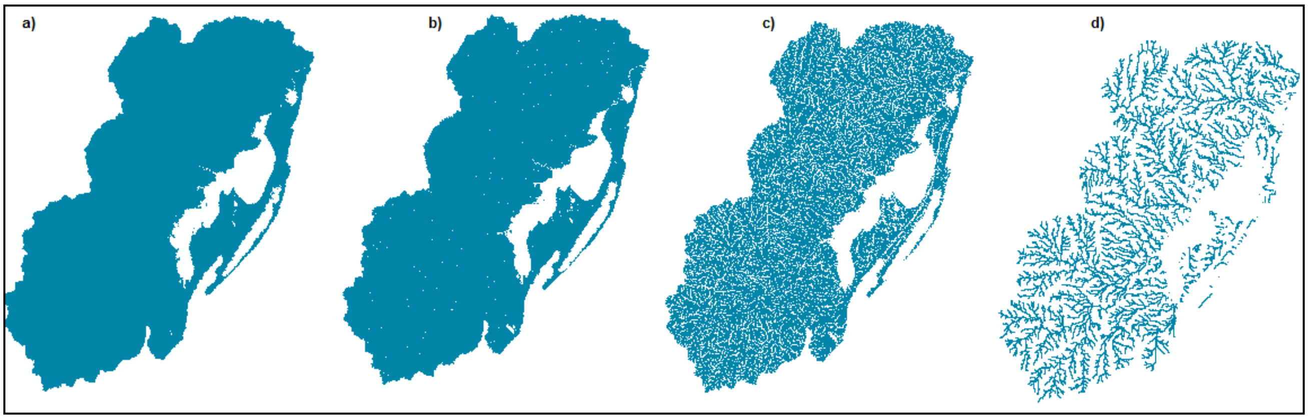


Figure 7 - Hydrography of the Mirim Lagoon Basin obtained with different thresholds: (a) 100, (b) 250, (c) 500 and (d) 1000.

Figure 8 shows the representation of the fluvial hierarchy of the Mirim Lagoon basin.

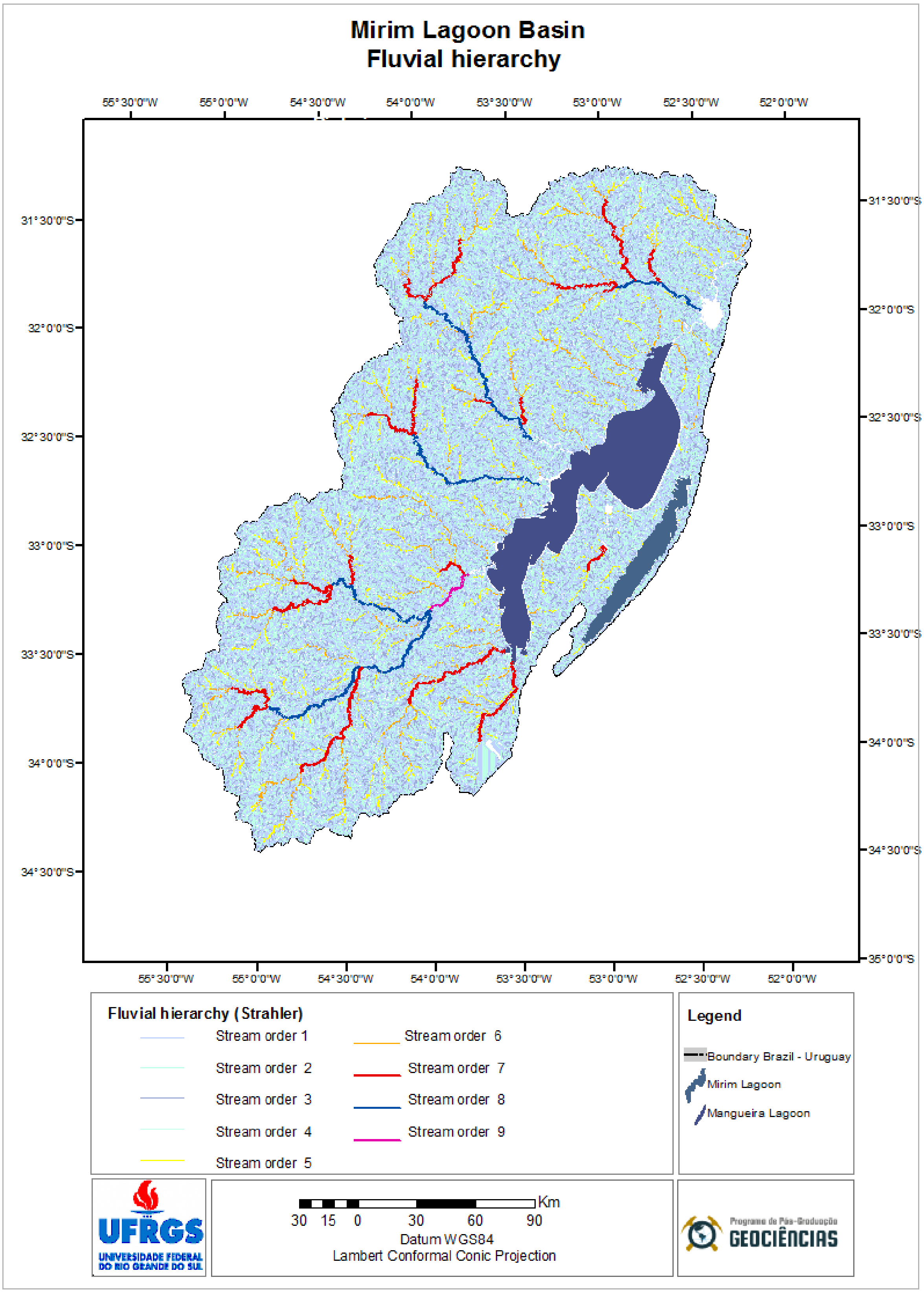


Figure 8. Fluvial Hierarchy of Mirim Lagoon Basin.

Figure 9 shows the eight sub-basins of the Mirim Lagoon Basin. In this figure, the hydrography representation is more generalized due to the presentation scale.

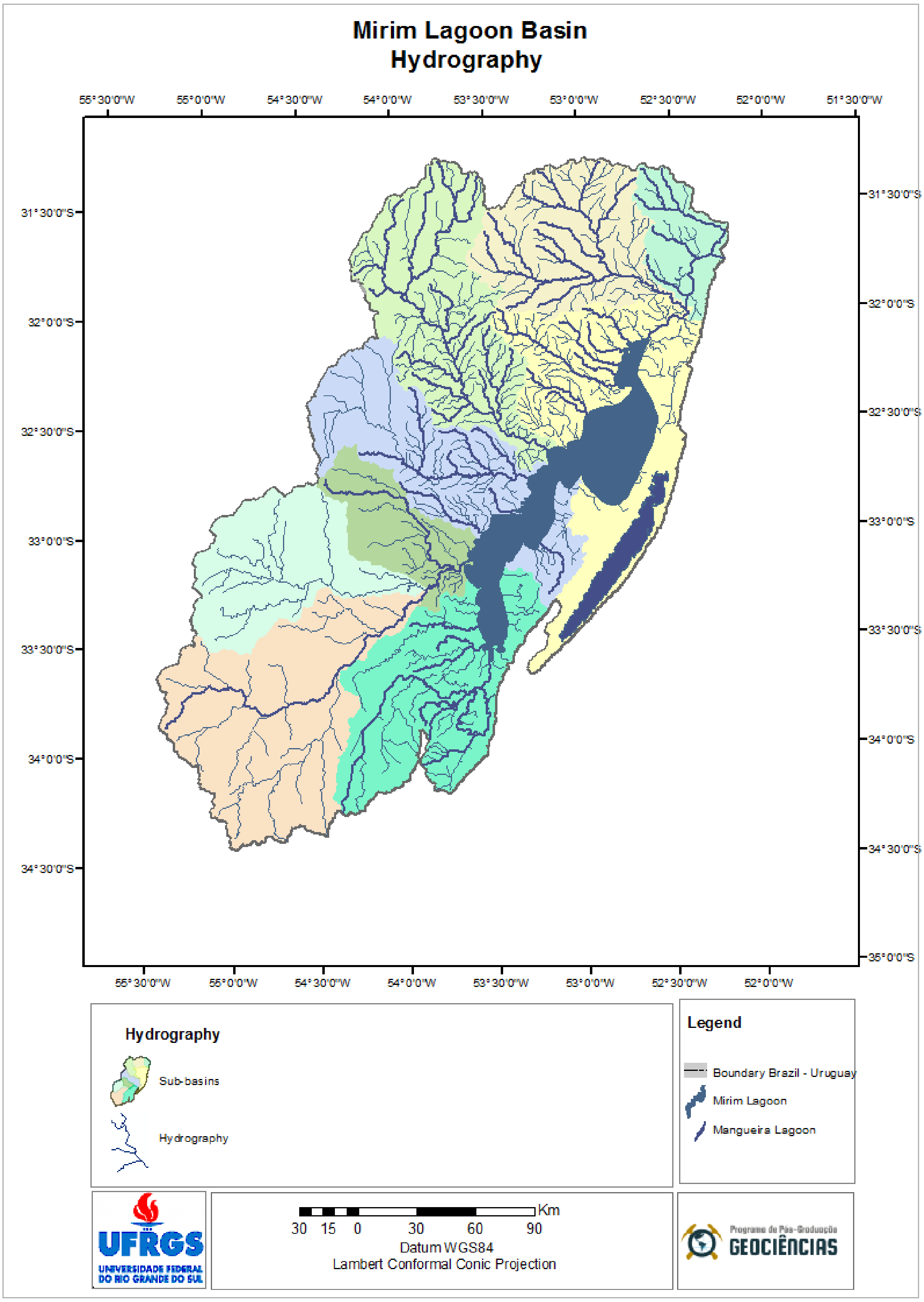


Figure 9. Hydrography of Mirim Lagoon Basin.

Table 5 shows the results of the basin geometry parameters calculations. The circularity ratio of 0.308 indicates that the Mirim Lagoon Basin tends to be more elongated, which favors the flow process. Also, the shape factor of 0.3 and the compactness coefficient of 1.81 indicate that the basin is not subject to large floods (Horton, 1932).

Table 5. Geometry Parameters

| | |
|---|---|
| Total Basin Area($Km^2$) | 58407.7820437 |
| Total Basin Surface Area($Km^2$) | 58616.7901219 |
| Total Basin perimeter(Km) | 1475.35392948 |
| Basin Length (Km) | 402.474 |
| Main Channel Length (Km) | 441.966 |
| Fitness Ratio | 0.299566084564 |
| Form Factor | 0.329707542763 |
| Shape Factor Ratio | 3.03299097018 |
| Relative perimeter | 36.199979528 |
| Length Area Relation | 960.927807531 |
| Rotundity coefficient | 2.38306422539 |
| Mean Basin Width | 132.698713566 |
| Drainage Texture | 97.5826865158 |
| Compactness Coefficient | 1.8136988604 |
| Circularity ratio | 0.308423445775 |
| Elongation ratio | 0.647917254732 |

The results of the drainage texture analysis are shown in table 6. The drainage density of 2.06 $km/km^2$ is considered low and indicates a permeable subsoil, and the basin has good drainage and fast flow capacity (Strahler, 1957).

Table 6. Drainage Texture Analysis

| | |
|---|---|
| Drainage density | 2.06054552518 (km/ $Km^2$) |
| Modified Drainage density | 2.05251314094 (km/ $Km^2$) |
| Stream frequency | 2.6956558481 (number/ $Km^2$) |
| Modified Stream frequency | 2.68514768737 (number/ $Km^2$) |

| | |
|---|---|
| Constant of channel maintenance | 0.485308374786(km2/km) |
| Modified Constant of channel maintenance | 0.487207599335(km2/km) |
| Infiltration Number | 5.55452159524 |
| Modified Infiltration Number | 5.51130091368 |
| Drainage Intensity | 1.30822435862 |
| Average Length of Overland Flow (Kms) | 0.242654187393 |
| Modified Average Length of Overland Flow (Kms) | 0.243603799668 |

Table 7 shows the results of the basin relief calculations. The altitude in the study area ranges from 0 to 513 m. The lowest altitudes are located to the east and the highest ones to the north and northwest (figure 10). The slope ranges from 0 to 45%, however, values below 8% predominate. In these areas, the relief can be classified as flat to soft wavy. Figures 11 and 12 represent the slope and orientation (aspect) of the Mirim Lagoon Basin, respectively.

Table 7. Basin Relief

| | |
|---|---|
| Height of Basin outlet (m) | 1.0 |
| Maximum Height of basin(m) | 513.0 |
| Total Basin Relief (H) m | 512.0 |
| Relief Ratio | 0.00127213186442 |
| Relative Relief Ratio | 0.0347035372171 |
| Gradient Ratio | 0.00127213186442 |
| Ruggedness Number | 1.05499930889 |
| Melton Ruggedness Number | 2.21547926443 |
| Modified Melton Ruggedness Number | 2.21115687577 |
| Terrain Undulation Index | 1.00391343865 |

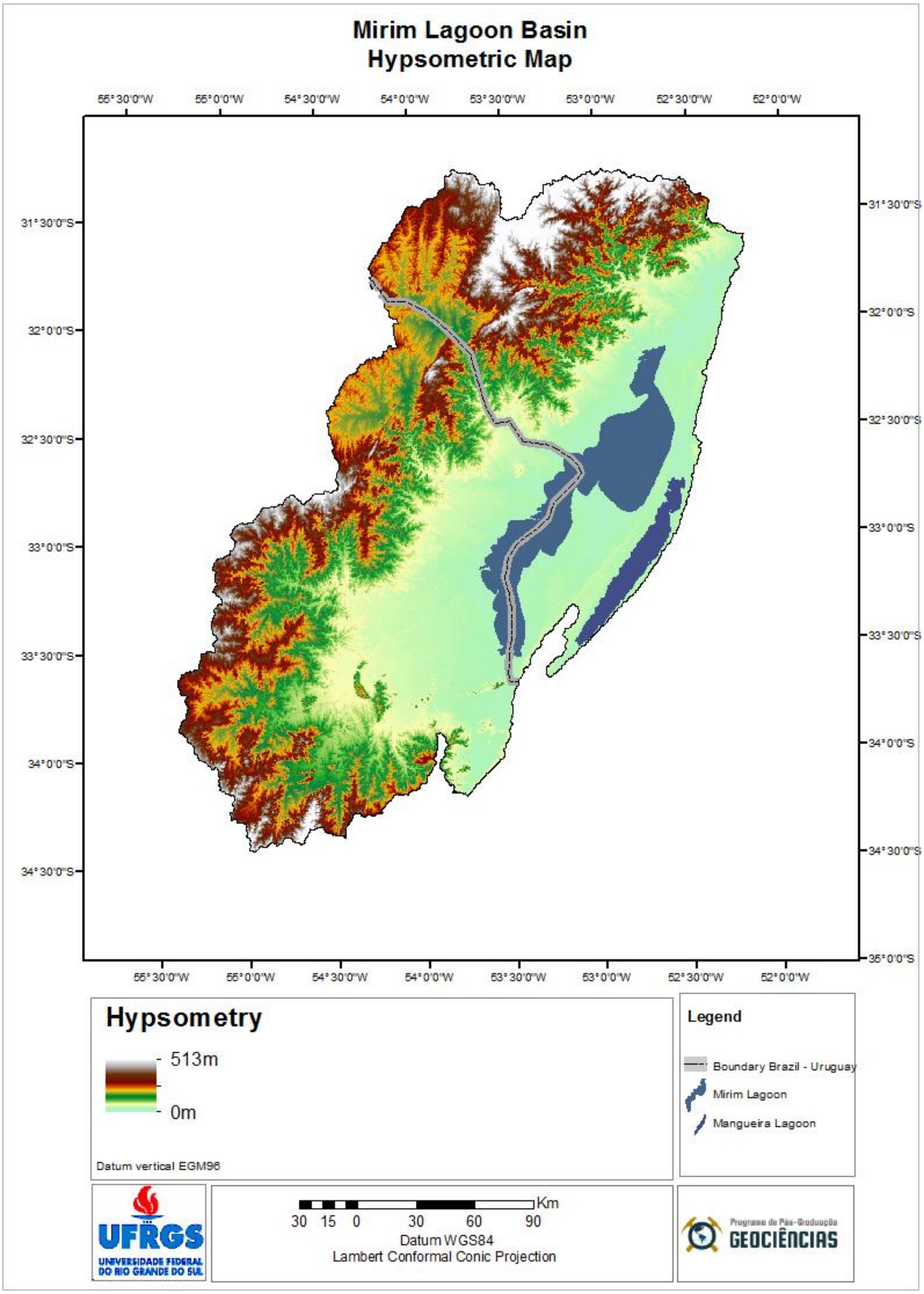


Figure 10. Hypsometric Map of Mirim Lagoon Basin.

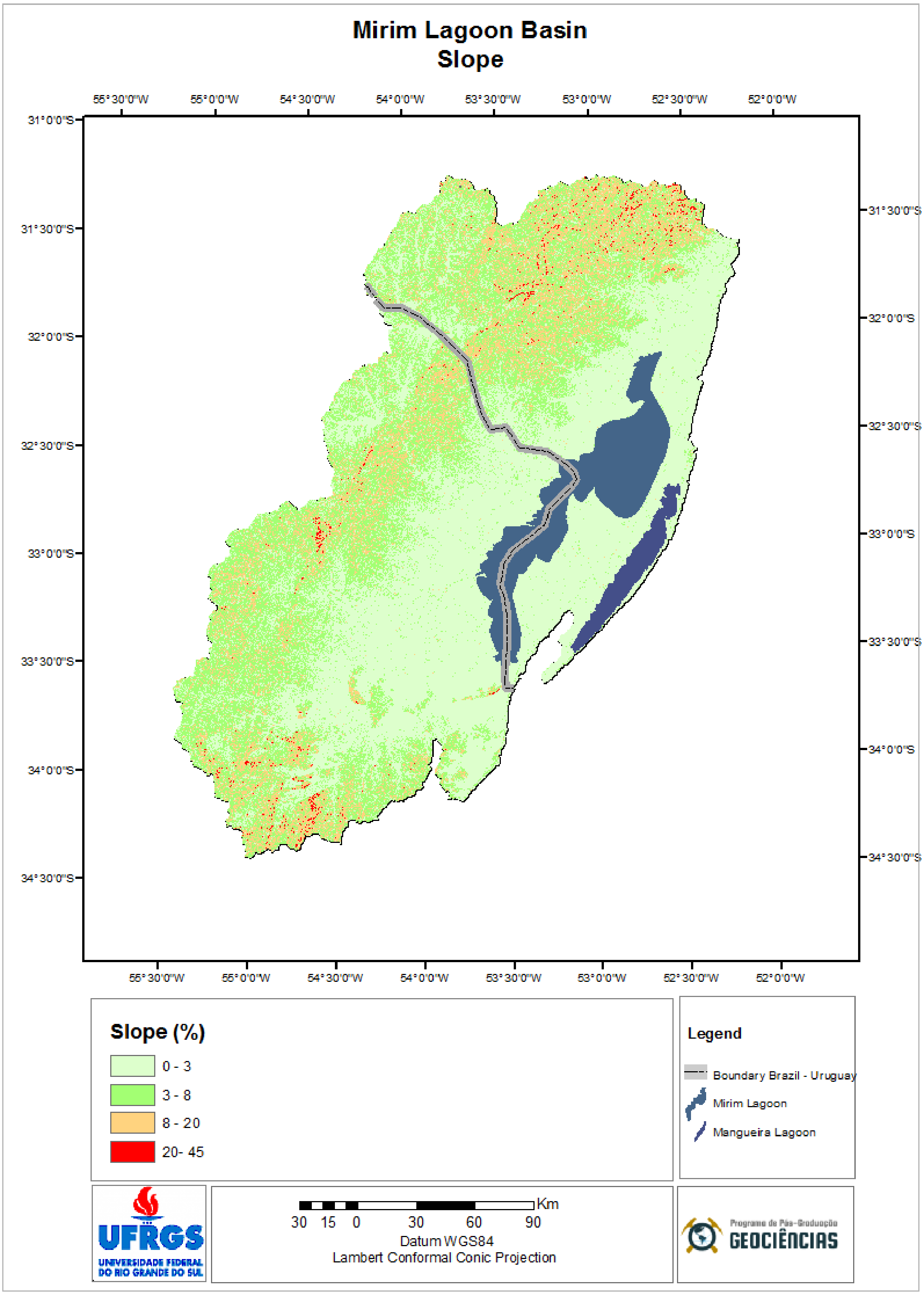


Figure 11. Slope of Mirim Lagoon Basin.

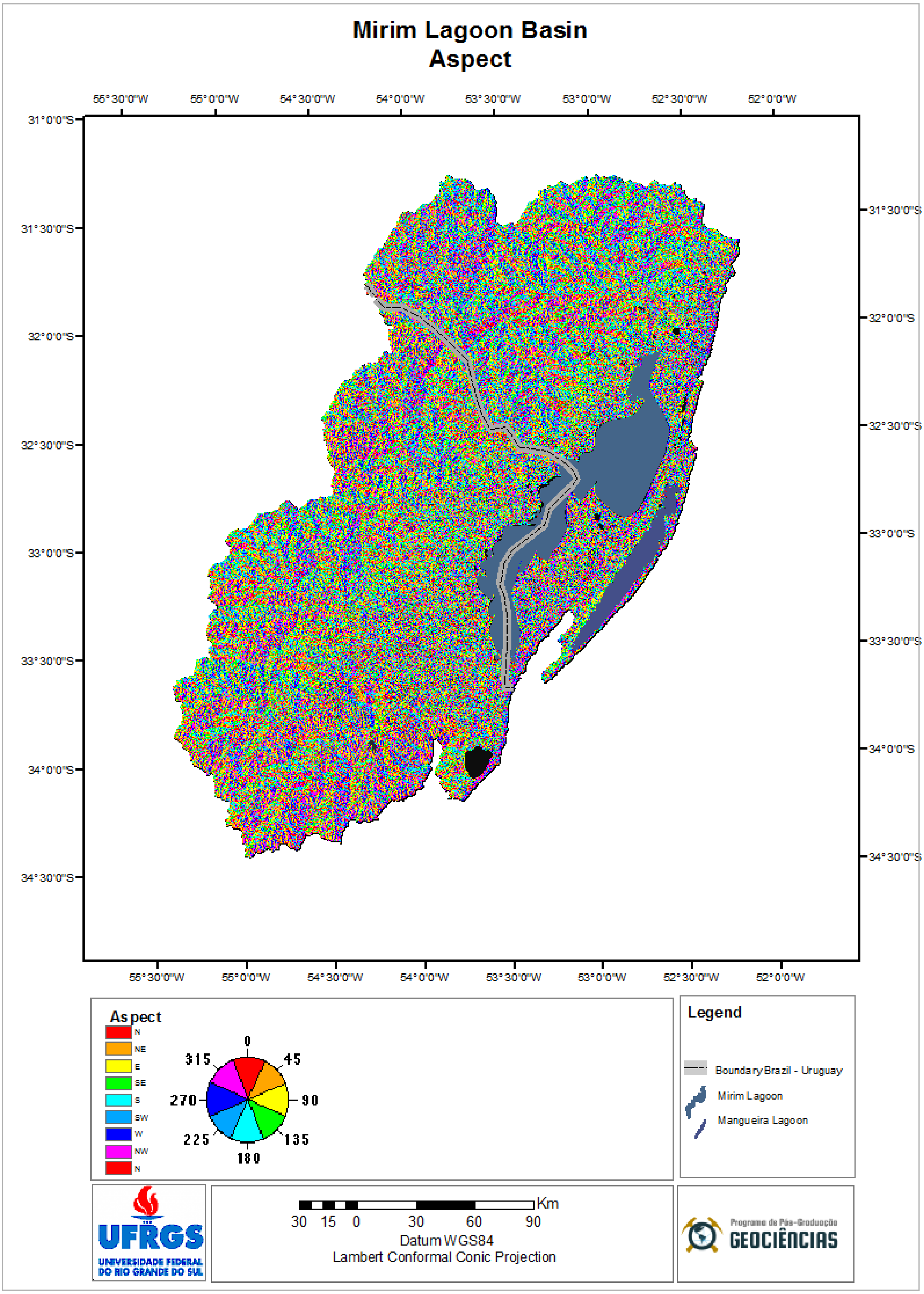


Figure 12. Aspect of Mirim Lagoon Basin.

## 4.2 Hypsometric analysis of Mirim Lagoon Basin

In case of hypsometric analysis, the results are given as relative height (h/H), relative area (a/A), relative surface area (as/As) and relative volume (v/V) ratios (tables 8 and 9). The results of hypsometric integrals and curves calculated based on map projected area and surface area are approximately similar and depend on the terrain undulation and DEM resolution. But the volumetric integral value and the shape of the volumetric curve shows more accurate evidences about the amount of the remaining rock mass waiting for denudation in the basin compared to the hypsometric integral values. The difference between the three types of hypsometric measurements is clear from the shape of the curves shown in figure 13.

Table 8 - Results of hypsometric analysis of the Mirim Lagoon Basin

| | |
|---|---|
| Minimum Height(m) | 1.0 |
| Maximum Height(m) | 513.0 |
| Incremental Elevation Interval(m) | 30 |
| Total Basin Height(H)(m) | 512.0 |
| Total Basin area($Km^2$) | 58407.7820437 |
| 1.Hypsometric Integral (Height_Area Ratios) | 18.9478610013 |
| 2.Hypsometric Integral (Height_Surface Area Ratios) | 19.0025313573 |
| 3.Hypsometric Integral (Height_Volume Ratios) | 17.8101989014 |

Table 9. Ratio

| (h/H)ratio | (a/A)ratio | (as/As)ratio | (vol/VOL) ratio |
|---|---|---|---|
| 0.0000000 | 1.0000000 | 1.0000000 | 1.0000000 |
| 0.0584767 | 0.6700468 | 0.6711005 | 0.7631675 |
| 0.1169535 | 0.5548515 | 0.5561401 | 0.5813494 |
| 0.1754302 | 0.4610033 | 0.4623392 | 0.4299322 |
| 0.2339070 | 0.3593529 | 0.3606328 | 0.3074696 |
| 0.2923837 | 0.2673977 | 0.2684858 | 0.2145481 |
| 0.3508604 | 0.1966027 | 0.1974607 | 0.1459089 |
| 0.4093372 | 0.1443809 | 0.1450255 | 0.0953571 |
| 0.4678139 | 0.1016463 | 0.1021115 | 0.0588497 |
| 0.5262906 | 0.0662808 | 0.0666052 | 0.0340386 |
| 0.5847674 | 0.0397285 | 0.0399489 | 0.0184478 |
| 0.6432441 | 0.0229945 | 0.0231334 | 0.0093445 |
| 0.7017209 | 0.0129359 | 0.0130141 | 0.0041000 |
| 0.7601976 | 0.0060642 | 0.0060986 | 0.0013294 |
| 0.8186743 | 0.0017346 | 0.0017447 | 0.0002425 |
| 0.8771511 | 0.0001831 | 0.0001847 | 0.0000196 |
| 0.9356278 | 0.0000119 | 0.0000121 | 0.0000009 |
| 0.9941045 | 0.0000000 | 0.0000000 | 0.0000000 |
| 0.9980030 | 0.0000000 | 0.0000000 | 0.0000000 |

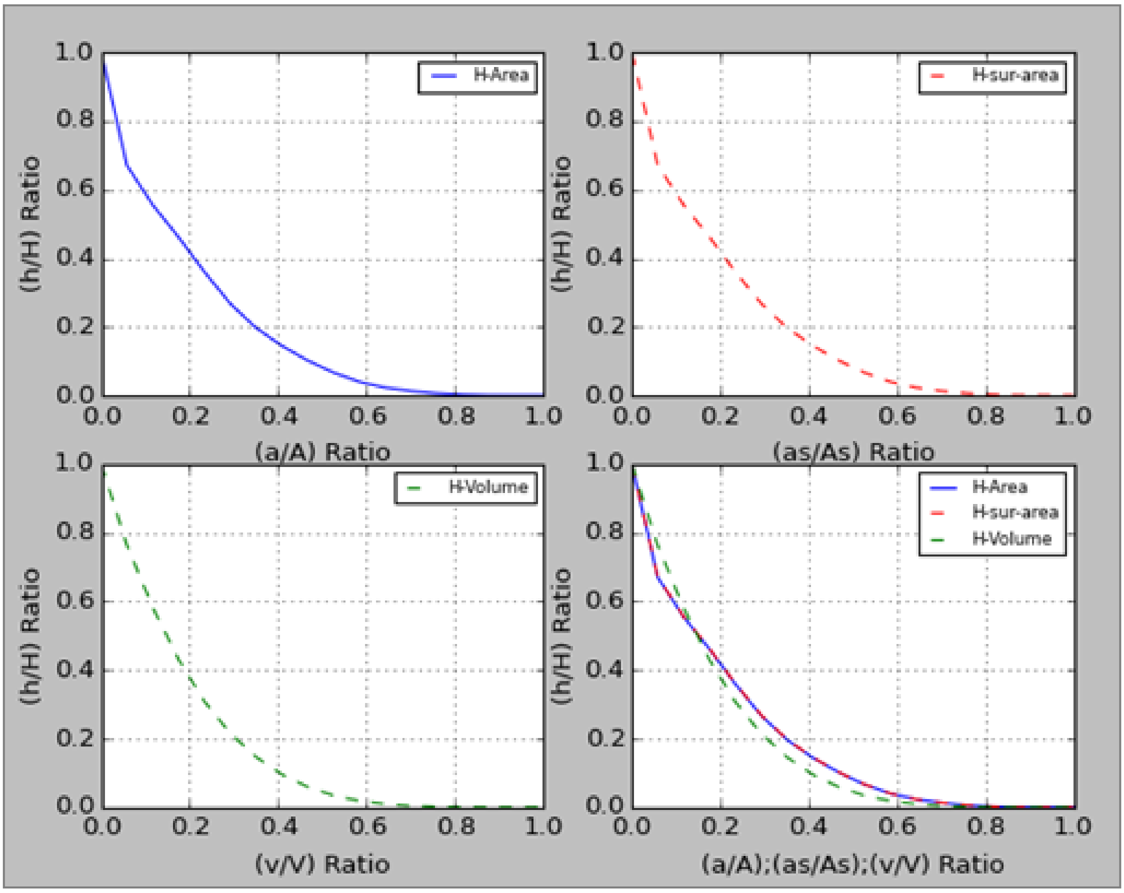


Figure 13. Graphs of hypsometric and volumetric curves of Mirim Lagoon Basin.

The hypsometric curve describes the distribution of elevations across an area of land, which has been used to evaluate the evolutionary status of landforms. Hypsometric curves are related to geomorphic and tectonic evolution of drainage basins in terms of their forms and processes (Schumm, 1956; Strahler, 1964). A useful attribute of the hypsometric curve is that drainage basins of different sizes can be compared with each other because area and elevation are plotted as functions of total area and total elevation. That is, the hypsometric curve is independent of differences in basin size and relief (Strahler, 1952).

The HI is expressed as a percentage and is an indicator of the remnant of the present volume as compared to the original volume of the basin and is also an indication of the cycle of erosion. The cycle of erosion is defined as the total time required for reduction of a land topological unit to the base level, i.e., the lowest level.

Strahler (1952) has classified three types of landforms on the basis of shapes of the hypsometric curve, each denoting the three typical stages of basin dissection:

-the monadnock or old stage if HI≤35%, in which the basin is fully stabilized;

-the equilibrium or mature stage if 35%<HI<60%, in which the basin development has attained steady state condition;

-the inequilibrium or young stage if HI≥60%, where the basin is highly susceptible to erosion and is under development.

The hypsometric integral (HI) values obtained for the Mirim Lagoon basin is presented in table 8. The HI value of the Mirim Lagoon basin is computed to be 18,94 %, which reveals that basin is in the later old (Monadnock) stage.

## 5. CONCLUSIONS

The goals of this study, which include the automatic generation of hydrography and the acquisition of the morphometric and hypsometric parameters of the Mirim Lagoon Hydrographic Basin with the use of SRTM data, were achieved through the procedures that encompass the SRTM DEM generation activities, and the definition of the appropriate map projection for the study area, The use of quantitative and qualitative methods to characterize a river basin allows a greater understanding of its dynamics, therefore the use of many parameters is very important.

The SRTM DEM of the Mirim Lagoon Hydrographic Basin was generated by using 15 SRTM images, version 3, band C, with a spatial resolution of 1 arcsecond, approximately 30 meters. These images were computationally processed, in order to guarantee a hydrologically consistent model.

The map projection defined for the study area, and used in all analyses and representations, was the Lambert Conformal Conic Projection with Two Standard Parallels (34º 12’ S and 31º 48’ S). The standard parallels were determined using a Kavrayskiy's constant value of 5.

The automatic hydrography acquisition was obtained from the SRTM DEM, from which the flow directions were taken, and the cumulative flow was calculated. The thresholds of 100, 250, 500 and 1000 were established for the contribution area, which allowed the generation of drainage networks with different degrees of detail.

From the spatial analysis on the generated SRTM DEM and implemented computational routines, the morphometric and hypsometric parameters of the Mirim Lagoon Basin were calculated. The drainage network of the basin is composed of 143969 channels, classified as ninth-order (Strahler, 1952) and there is a predominance of small order channels.

The drainage pattern of the basin is dendritic, indicating an absence of structural or tectonic control, and the value of 4.3 obtained for the mean bifurcation ratio corresponds to a very dissected drainage basin (Strahler, 1957). The Mirim Lagoon Basin tends to be more elongated (circularity index = 0.308), thus favoring the flow process. In addition, the basin is not subject to large floods (Horton, 1932), as indicated by the form factor (0.3) and the compactness coefficient (1.81), and the low drainage density (2.06 km/Km$^2$) indicates a permeable subsoil, with good drainage and fast drainage capacity (Strahler, 1957). Regarding basin relief, the altitude range is 513 m (from 0 to 513m) and there is a predominance of values below 8% for the slope, which ranges from 0 to 45%. Additionally, the HI value (18.94%) reveals that the basin is in the later old stage (Monadnock).

It is also worth noting that Geoprocessing techniques in a GIS environment, with the use of SRTM DEMs, were efficient in the morphometric and hypsometric analysis, in obtaining the hydrology automatically in a large hydrographic basin, and in the representation of the relief. These analyses and representations are of great importance in any hydrological and environmental research, proving to be a practical and viable alternative to minimize costs and time in the work execution.

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## AUTOMATIC DETERMINATION OF KNICKPOINTS IN THE MIRIM LAGOON BASIN, REGION OF CROSS-BORDER HYDRIC RESOURCES (BRAZIL AND URUGUAY, SOUTH AMERICA)

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ABSTRACT

In fluvial geomorphology, the term knickpoint (Kp), defines steep sections in the longitudinal profile of a water stream. Their position and distribution is an essential indicator for the analysis of the evolution of landscapes severely marked by fluvial erosion. This work presents the automatic determination of both hydrography and knickpoints in the Mirim Lagoon Basin, a cross-border basin located in the Atlantic coast of South America, between 31°S and 34°30'S, and 52°W and 55°30'W, covering an area of 58,407.78 $km^2$, both in Brazilian (47%) and Uruguayan (53%) territories. The results were obtained using geoprocessing techniques such as the ArcGis program, version 10.2.2, with spatial analyses and data manipulation tools. Information from the Shuttle Radar Topographic Mission (SRTM) was used for determination of hydrography and knickpoints. The hydrography was obtained with the Model Builder and hydrologic tools of ArcGis. The knickpoints were determined through the Knickpoint Finder, a script in Python language integrated to the ArcToolbox of the ArcGis program. Fifteen SRTM images were used for the covering of the Mirim Lagoon Basin. The results demonstrated that the geoprocessing in SIG environment with digital models of SRTM elevation data presented in this work are efficient for the determination of hydrography and knickpoints in a wide hydrographic basin. Therefore, the knickpoints determination brings a contribution to the knowledge on the Mirim Lagoon Basin evolution.

**Keywords:** Knickpoints; SRTM; GIS; Fluvial Geomorphology.

## 1.INTRODUCTION

Water streams are influenced by crustal tectonic modifications, reacting promptly to deformative processes. So, approaches which explore attributes related to profiles or routes of water streams are invaluble for the detection and assessment of deformations (Etchebehere et al., 2004; Volkov et al., 1967, Schumm, 1993).

This work presents the automatic determination of hydrography based on the model builder and hydrologic tools of the ArcGis program and the use of a technique named "Relation of Declivity and

Extension - RDE" (Hack, 1973; Etchebehere et al., 2004), also known as "Hack Index", for the automatic detection of knickpoints in the drainage based on SRTM images and geoprocessing techniques based on the Knickpoint Finder (Github, 2014), a script in language Python integrated to the ArcGis version 10.2.2. This technique allows a fast, efficient and low-cost assessment for detection of anomalous hydrographic sectors in large regions.

Several studies dealt with the drainage analysis for the identification of anomalies, being the pioneering works by Horton (1945), Strahler (1952), Howard (1967) and Hack (1973) noteworthy examples. Afterwards, several authors have worked on the determination of knickpoints and anomalies in fluvial profiles, among them Gardner (1983), who presented an experimental study of knickpoints and longitudinal evolution in cohesive homogeneous material. Seeber & Gornitz (1983) studied river profiles along the Himalayan arc as indicators of active tectonics. Keller & Pinter (1996) investigated active tectonics, earthquakes, uplift and landscape in the San Gabriel Mountains, southern California, which displays unusual high values, that have been linked to high uplift rates. Etchebehere et al. (2004, 2006) applied the "Declivity-Extension Relation–RDE" index in the Rio do Peixe Basin (São Paulo State) for the detection of neotectonic deformations. Harbor et al. (2005) studied a capturing variable knickpoint retreat in the central Appalachians, USA. Bishop et al. (2005) studied a knickpoint recession rate and catchment area of uplifted rivers in Eastern Scotland. Crosby & Whipple (2006) studied a knickpoint initiation and distribution within fluvial networks, finding 236 waterfalls in the Waipaoa River, North Island, New Zealand. Salamuni et al. (2013) applied the knickpoint finder tool for the survey of geosites with potential touristic significance. Nascimento et al. (2013) pointed the neotectonic evidences in the Serra do Mar relief, Paraná State, Brazil, through the definition of knickpoints. Queiroz et al. (2015) analyzed drainages with the Knickpoint Finder software applied both in morphotectonic and neotectonic studies.

One of the technologies used in the analysis of geomorphologic systems is the computational treatment of data obtained by remote sensing, especially the data supplied by interferometric radars as, for instance, those obtained by SRTM (Shuttle Radar Topography Mission). These data permit the elaboration of a topographic model for the Earth surface and provide a base for studies in several units of geomorphologic analyses (geomorphologic systems), such as hydrographic basins.

The most usual technique for derivation of relief morphologic attributes is based on digital elevation models (DEMs) and digital hydrographic net. Computational routines are applied on those data for acquisition of the hydrography and drainage anomalies. The DEMs and the hydrographic nets must have both morphologic and hydrologic consistency for validation of the results obtained in the morphometric analyses.

In fluvial geomorphology the term knickpoint (Kp) or declive rupture is applied to steep sections in the longitudinal profile of a water flow. Their position and distribution are essential markers for the interpretation of the fluvial net incision and evolution of landscapes markedly dissected by fluvial erosion (Ferreira et al., 2010). So, the reflection on the distribution of the knickpoints in the hydrographic basins is pivotal in studies on landscape evolution, operating as an essential method in fluvial geomorphology studies (Goudie, 2004; Ferreira et al., 2010; Hayakawa & Oguchi, 2006, Crosby et al., 2006).

Florenzano (2008) argues that the longitudinal profile of a drainage channel represents the relation between altimetry and the channel's length in different points between the spring and its mouth. In general of parabolic shape, the typical profile is concave (considering the equilibrium between erosion, transport and deposition processes), with high declivities toward the spring, and low ones downstream. The declivity of the channel is in a determinate point tangent to the profile in this point. The figure 1 outlines a knickpoint, which defines the mobile boundary between the adjustment and disadjustment sector of the channel. The lighter arrows indicate the backward movement of the knickpoint.

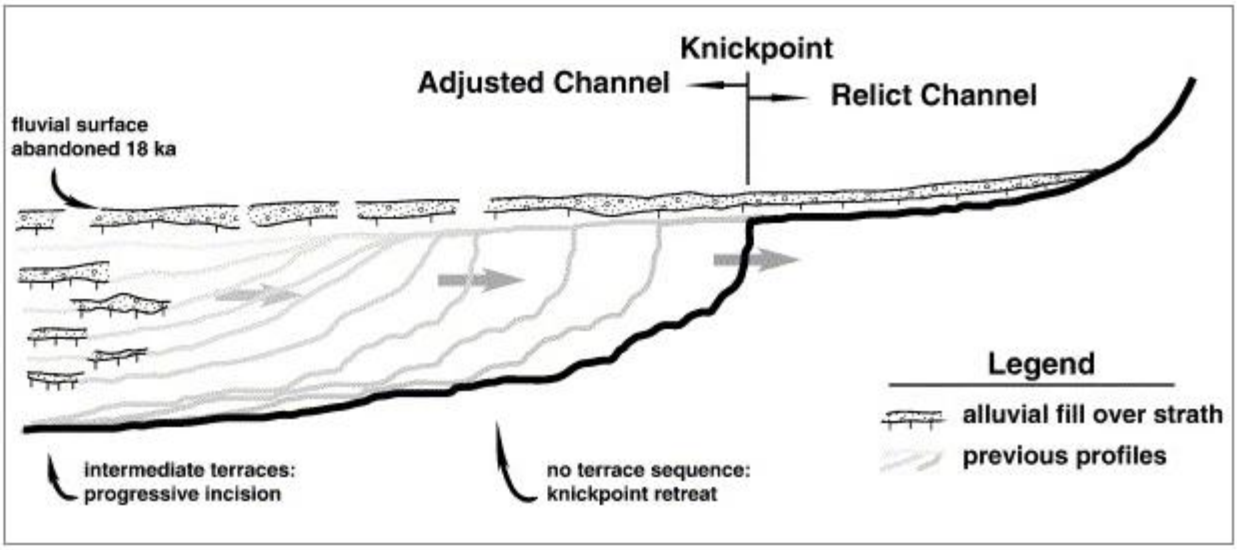
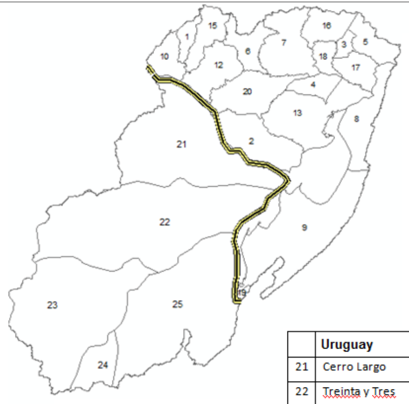



Figure 1 – Schematic representation of a knickpoint. Source: Crosby & Whipple (2006).

In this context the present work, whose objective is to determine automatically both the hydrography and knickpoints in the Mirim Lagoon presents a contribution to the evolution of the Mirim Lagoon Basin. It is inserted in a research project which aims also the analysis of the SRTM digital model of elevation using GNSS data for validation of the orthometric altitude and assess the morphometry and hypsometry of the study area.

## 2.STUDY AREA AND GEOLOGICAL SETTING

The Mirim Lagoon Basin lies in the Atlantic coast of South America between 31°S and 34°30'S, and 52°W and 55°30'W, corresponding to an area of 58,407.78 km$^2$, being 47% in Brazilian territory and 53% in Uruguayan territory being, therefore, a cross-border basin. In the Brazil it influences 20 municipalities and in the Uruguay, five departments. The figure 2 presents the municipalities and departments bathed by the Mirim Lagoon Basin, and in the figure 3 is its location.



| | Brazil |
|---|---|
| 1 | Hulha Negra |
| 2 | Jaguarão |
| 3 | Morro Redondo |
| 4 | Pedro Osório |
| 5 | Pelotas |
| 6 | Pinheiro Machado |
| 7 | Piratini |
| 8 | Rio Grande |
| 9 | Santa Vitória do Palmar |
| 10 | Aceguá |
| 12 | Pedras Altas |
| 13 | Arroio Grande |
| 15 | Candiota |
| 16 | Canguçu |
| 17 | Capão do Leão |
| 18 | Cerrito |
| 19 | Chuí |
| 20 | Herval |

| | Uruguay |
|---|---|
| 21 | Cerro Largo |
| 22 | Treinta y Tres |
| 23 | Lavalleja |
| 24 | Maldonado |
| 25 | Rocha |

Figure 2 – Municipalities (Brazil) and Departments (Uruguay) which make up the Mirim Lagoon hydrographic basin.

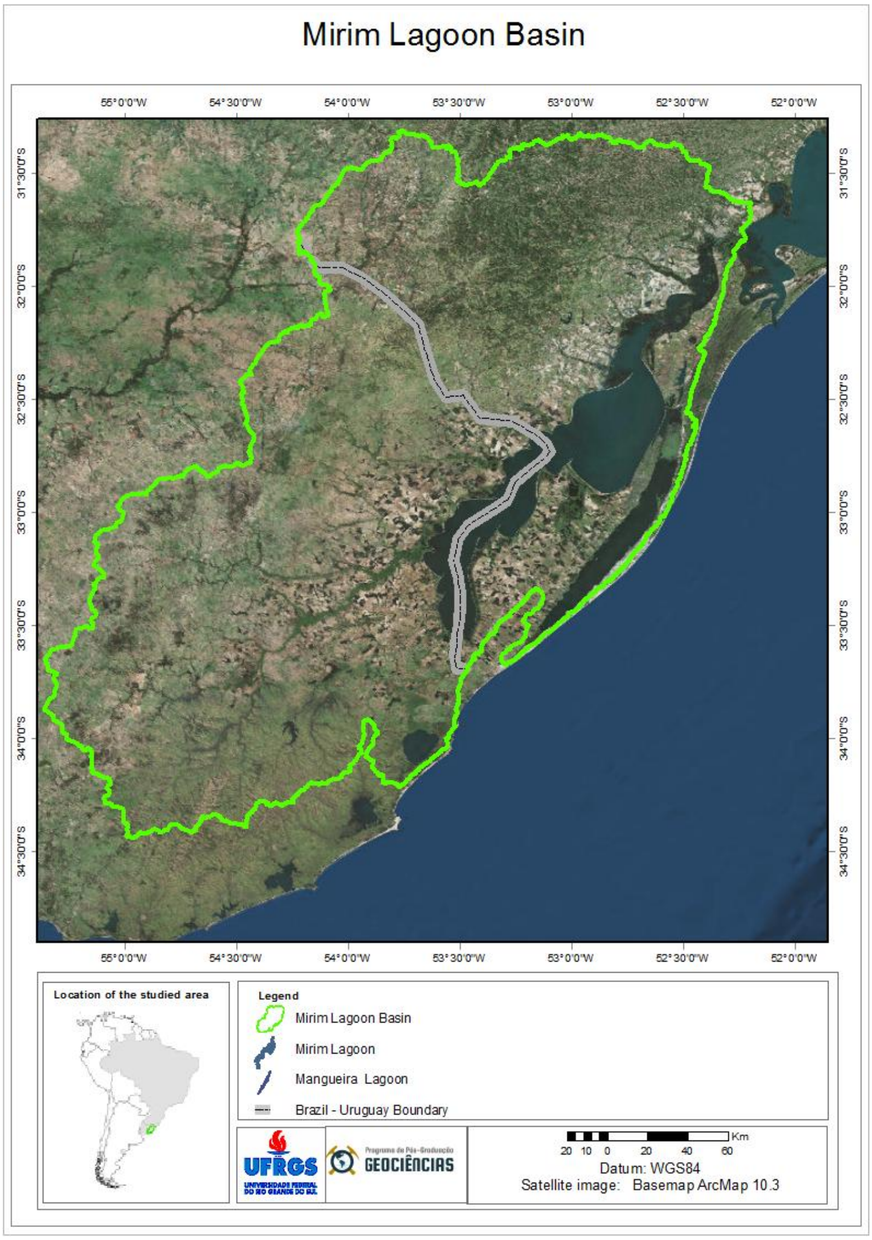



Figure 3. Location of the study area.

The Mirim Lagoon Basin is described as a paleogeographic unit resulting from extensional efforts which resulted in fractures due to the eruption of volcanic lavas and the sinking of wide rocky masses. These phenomena began 150 Ma ago during the Gondwana breakup which lead to the opening of the Atlantic Ocean. The flooding area of the Mirim Lagoon results from the sinking process of Middle–Upper Jurassic which created the tectonic trench of Mirim. During the Cenozoic, the continuous and moderate sinking process along with slow vertical movements in the Tertiary and Quaternary, originated the low altitudes and the higher and extensive interfluves. The interaction between the geologic development with complex paleoclimatic elements, mainly during the Quaternary, resulted in the present relief, represented by the plains and inselbergs. The coastal belt results from marine transgressions, which originated most of the marshes and lagoons during the Holocene. The geologic basement of the hydrographic basin is composed by a complexity of structures of the South American Shield. The western zone is characterized by a positive orogenic trend that at the end of the Cenozoic, originated low altitude relieves (hills and mountain chains) reaching, no more than 520 m. In the eastern sector of the basin, the chemical intemperism began in the Permo-Carboniferous and lasted up to the Jurassic, allowing the accumulation of sediments along the coast (Probides, 2000; Montaña & Bossi, 1995, Steike & Sato, 2008).

The study area includes the sedimentary deposits of the Pelotas Basin and the adjacent basement that outcrops in the western region and is composed by rocks of the Uruguaio-Sul-Rio-Grandense Shield, which belongs to the Mantiqueira Province and Paraná Basin rocks. The rocks of the Sul-Rio-Grandense Shield were generated in the Brasiliano Cycle (Neoproterozoic–Early Paleozoic). The Paraná Basin is a intracontinental basin developed between the Late Ordovician and Late Cretaceous (Rosa, 2009).

According to Rosa (2017), Tomazelli et al. (2000) and Villwock et al. (1986), the Pelotas Basin coastal plain, located in southern Brazil and in northern Uruguay, has the most complete record of Quaternary events along the Brazilian coast. The Pelotas Basin has an area of approximately 210000 $km^2$. It borders the Santos Basin to the north, through Florianópolis High and Punta del Este Basin to the south, through Polonio High, in Uruguay. The Pelotas Basin was formed due to tectonic movements associated with the opening of the South Atlantic Ocean. The basement is composed of Uruguayan-Sul-Rio-Grandense Shield, Santa Catarina Shield and the Paraná Basin strata. In the figure 4 the South Atlantic coastal plain map is presented.

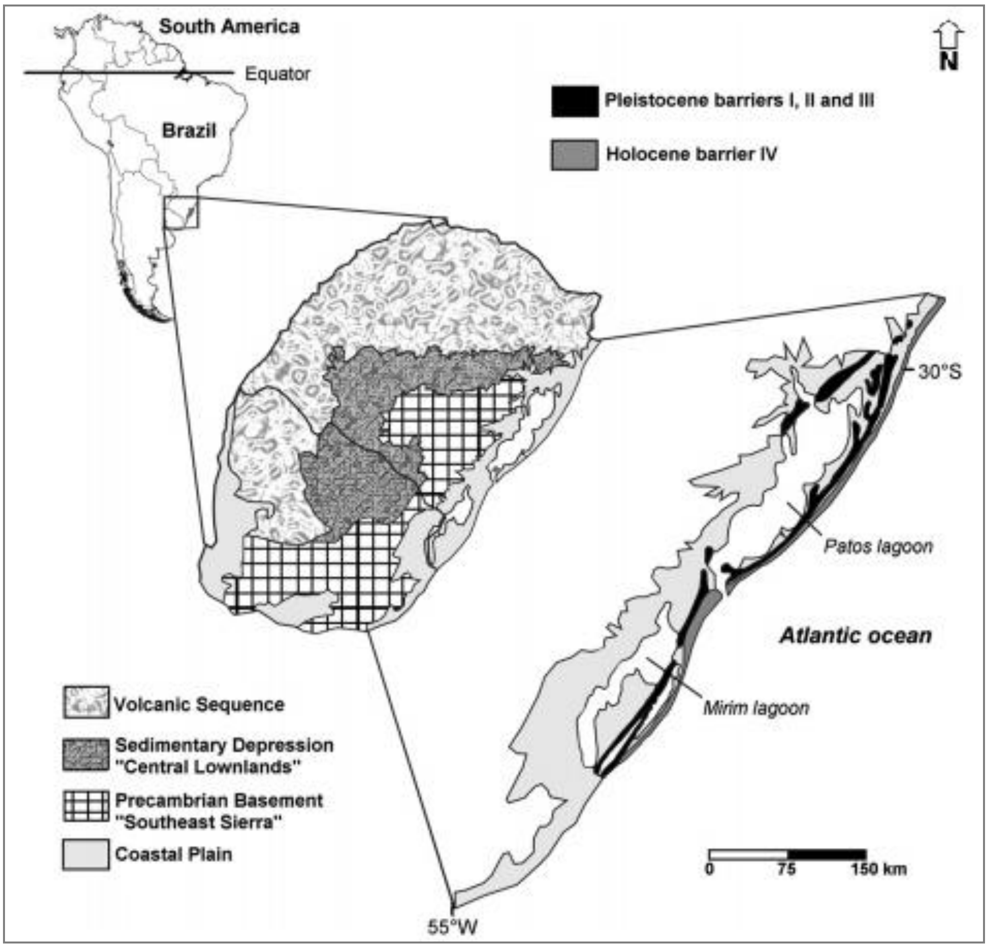



Figure 4 - South Atlantic coastal plain map. Modified from Mäder et al. (2013).

This large lowland embraces a great number of coastal water bodies, some of them of large dimensions, such as the Patos and Mirim lagoons. In the northern end of the coastal plain the adjacent highlands consist of Paleozoic and Mesozoic sedimentary and volcanic rocks of the Paraná Basin. In the southern section, igneous and metamorphic rocks of the Precambrian shield form lower highlands. To the north, the fades derived from high relief volcanic and sedimentary rocks of Paraná Basin are coarser and have a lithic composition. Southward, where the Precambrian shield is mainly formed by granitic rocks, the lithofacies are finer and have an arkosic composition. The deposition of the alluvial fan system had already began probably in the Tertiary (late Pliocene regression) and continued during all the Quaternary with an intensity controlled by cyclic changes from humid to arid conditions that occurred during this time.

The ramp morphology was a product of coalescence of adjacent fans and also the result of subsequent erosion and reworking, including the formation of terraces by marine and lagoonal waters operating on fans toes during sea-level highstands when the system was a fan-delta. From a geometric point of view the alluvial fan depositional system corresponds to a clastic wedge that thickens toward the interior of the Pelotas Basin. At present, the fades of alluvial fan system occur all over the western strip of the coastal plain adjacent to the highlands and especially to the south of the region where the alluvial fan apron surface has a succession of terraces formed by marine and lagoonal processes during the several Pleistocene transgressive events. Barrier-lagoon systems Quaternary glacio-eustatic fluctuations in the sea level produced great lateral displacements of the shoreline on the very low gradient of the Rio Grande do Sul coastal plain and continental shelf. Consequently, four barrier-lagoon systems were formed and preserved landward of the present coastline. Three barrier lagoon systems of Pleistocene age were identified on the coastal plain and named, from the oldest to the youngest, I, II and III, respectively. The Barrier I is the innermost, and consequently, older depositional system formed as a product of the first locally recognizable Pleistocene transgressive-regressive event. Barrier II was formed during the second local Pleistocene transgressive-regressive cycle and sediments are best preserved in the southern portion of the coastal plain, where they were responsible for the initial formation of Mirim Lagoon. Barrier III is the best preserved of the Pleistocene barrier systems. Its correlative sediments can be traced from north to south along the whole of the coastal plain and its development is clearly responsible for the final formation of the Patos and Mirim lagoons. Lagoonal Systems I, II and III all developed at the backbarrier setting between the mainland and the equivalent Pleistocene barrier systems. The most recent barrier-lagoon system of Rio Grande do Sul coastal plain (System IV) has been developed during the Holocene. At the final stages of the Post-Glacial Marine Transgression (PMT), when sea level was rising at low rates, the coastal evolution was strongly influenced by antecedent topography. Here the barriers have been subjected, over the long term, to two contrasting coastal processes: deposition in coastal bights leading to the formation of prograded barriers, and erosion along protruding stretches of coast leading to the formation of transgressive dunes, receded barriers and mainland beach barriers. The Holocene Lagoonal System has been developed in the backbarrier region between the Barrier IV and the mainland consisting of Pleistocene Barrier III. Moreover, during the Holocene highstand the flooding of the lowland situated between the Pleistocene barriers and the alluvial fan apron has re-established and broadened the Patos and Mirim lagoonal bodies. The coastal plain of Rio Grande do Sul has four clearly defined Quaternary barrier-lagoon systems. Each system was produced in the course of an interglacial high sea level, probably during the last 400 ka. Other Quaternary high sea-levels identified in the deep-sea sedimentary oxygen isotope record do not seem to be present along the coastal plain or, if so, their deposits were buried or not preserved. The geological history of Rio Grande do Sul coastal plain is a good example of how barrier-lagoon systems in wave-dominated setting may be developed and preserved during transgressive-regressive cycles of high frequency controlled by glacio-eustatic sea-level fluctuations.

## 3. METHODOLOGY

The methodology of this work is presented in the figure 5, and the phases c and d are detailed in the figures 7 and 8, respectively.

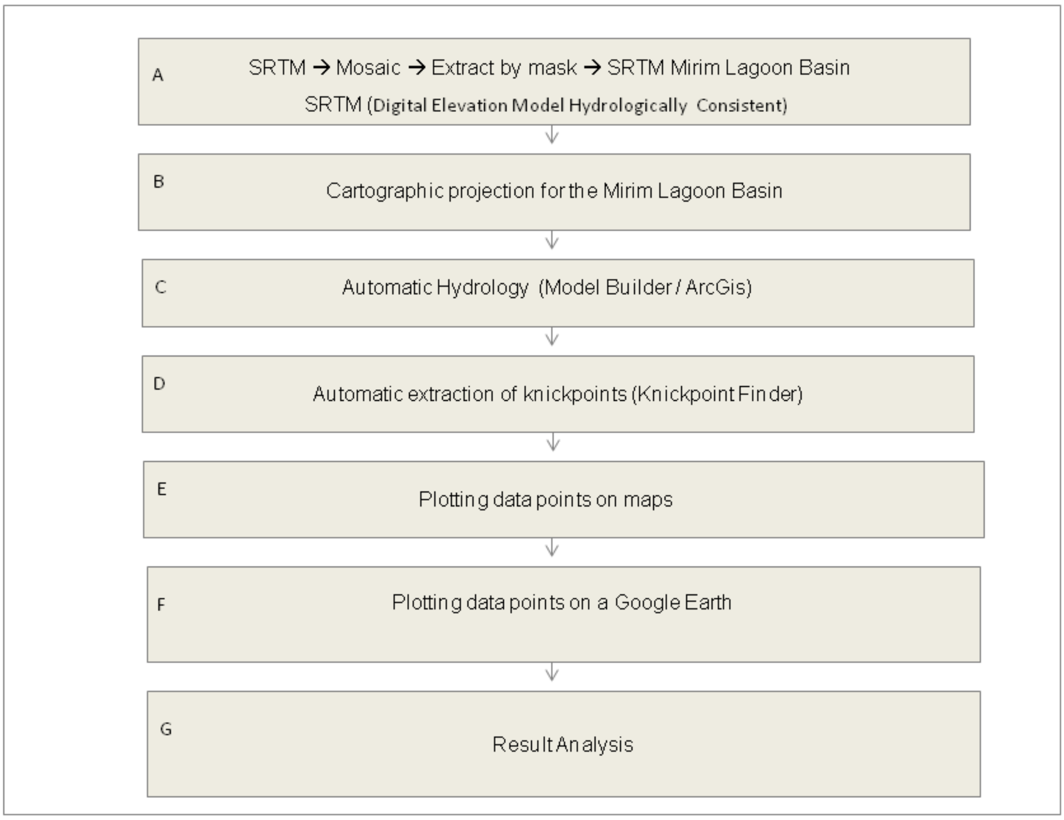



Figure 5 – Flow chart of the work methodology to obtain the automatic hydrography and determination of knickpoints in the Mirim Lagoon.

A) To the obtention of the mosaic in the Mirim Lagoon Basin 15 images of the Elevation Digital Model were used, obtained from the U.S. Geological Survey – USGS (http://earthexplorer.usgs.gov/) Shuttle Radar Topography Mission (SRTM) with spatial resolution of 30 m. The relation of the SRTM images that cover the Mirim Lagoon Hydrographic Basin is presented in the table 1:

Table 1 – SRTM images of the Mirim Lagoon Hydrographic Basin.

| | | |
|---|---|---|
| s32_w053_1arc_v3 | s33_w054_1arc_v3 | s34_w055_1arc_v3 |
| s32_w054_1arc_v3 | s33_w055_1arc_v3 | s34_w056_1arc_v3 |
| s32_w055_1arc_v3 | s33_w056_1arc_v3 | s35_w054_1arc_v3 |
| s32_w056_1arc_v3 | s34_w053_1arc_v3 | s35_w055_1arc_v3 |
| s33_w053_1arc_v3 | s34_w054_1arc_v3 | s35_w056_1arc_v3 |

The figure 6 presents the SRTM images of the Mirim Lagoon Basin and their respective amplitudes of latitude and longitude (a), the SRTM mosaic of the study area (b) and the SRTM mosaic with vector mask of the Mirim Lagoon Hydrographic Basin outline (c).

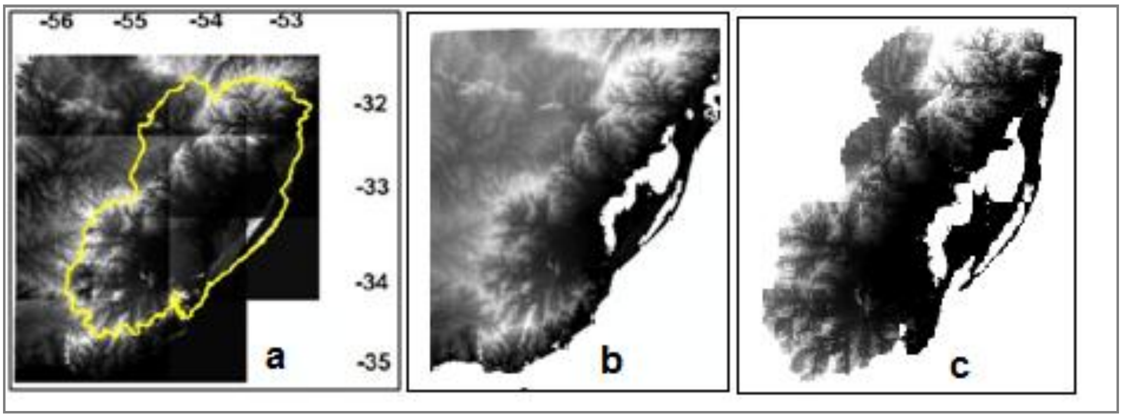



Figure 6 – SRTM coverage of the Mirim Lagoon Hydrographic Basin (a), SRTM mosaic (b) and SRTM mosaic vector mask with the Mirim Lagoon Hydrographic Basin outline (c).

B) Definition of the cartographic projection to the study area.

A Lambert Conformal Conic cartographic projection with two standard parallels was defined for the study area. The parallel standards were defined with a Kavrayskiy's constant (K) (Maling, 1992) and the projection was included in the ArcGis program and used in all the works in the study area and in the respective morphometric calculations.

C) Obtention of the automatic hydrography.

The automatic hydrography was obtained with a model developed in the Model Builder tool of ArcGis. The Model Builder creates models (representation simplified and manageable of reality) from fluxes that bring together a sequence of tools of the ArcToolbox and the data base. The stages for obtention of the automatic hydrography are demonstrated in the figure 7.

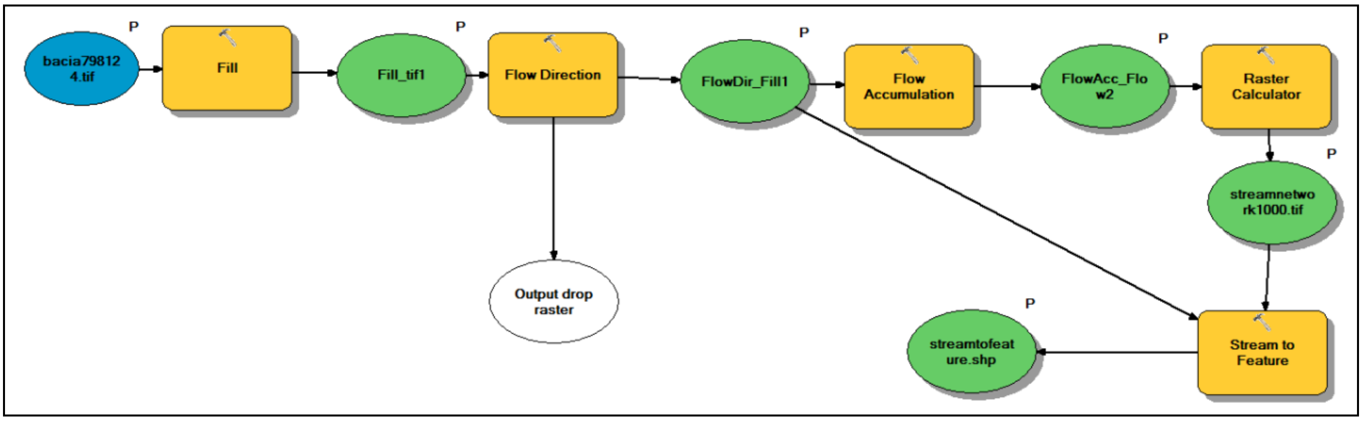



Figure 7 – Flow chart of the process for creation of the automatic hydrography in Mirim Lagoon Basin with the Model Builder tool of the ArcGis.

According to ESRI (2017) the first step in the hydrologic modeling tools in ArcGIS is to fill the elevation grid, starting with a surface that has no sinks. Sinks are areas of internal drainage, that is, areas that do not drain out anywhere. To calculate a drainage network, a grid must exist that is coded for the direction in which each cell in a surface drains. Flow accumulation is the next step in hydrologic modelling. In order to generate a drainage network, it is necessary to determine the ultimate flow path of every cell on the landscape grid. Flow accumulation is used to generate a drainage network, based on the direction of flow of each cell.

To obtain different levels of detail of the hydrography it must be applied a threshold defined with the Raster Calculator of the ArcGis Spatial Analyst relative to the flow accumulation. The lower the threshold, the higher is the detail of the hydrography, and the higher the threshold, the higher will be the cartographic generalization of the drainage.

D) The automatic determination of the knickpoints was carried out from computer tools in geoprocessing environment in the ArcGis version 10.2.2, with digital model of elevation SRTM, spatial resolution of 30 m and the use of the script Knickpoint Finder (Github, 2014) in Python language integrated to the ArcGis' ArcToolbox. Subsequently, the knickpoints with highest first order anomalies were choosen, summing up 594 knickpoints.

The Knickpoint Finder script is based on the stream length-gradient (SL) (Hack, 1973; Etchebehere et al., 2006; Queiroz, 2015). This parameter pertains to the longitudinal profiles of rivers or drainage stretches and is calculated by multiplying the slope gradient of the stretch of river by the distance between this stretch and the source of the river. A derivative of the Hack Index, the relative slope-extension (RDE) index, which gives an indication of the current energy in a particular drainage stretch and varies with the slope of its surface and the discharge of water at the end of the stretch. The total RDE index (RDEt), which in turn refers to the total length of a river, takes into account the total slope between the source and mouth and the natural logarithm of its entire length. The final goal, after measuring the indexes of various stretches and the indexes of their respective drainages, is to compare them to determine which stretches have anomalous slopes.

Acording to Queiroz (2015) the final goal, after measuring the RDEs indexes of various stretches and the RDEt indexes of their respective drainages, is to compare them to determine which stretches have anomalous slopes. RDEs/RDEt greater or equal to 2, the drainage stretch under analysis can be considered anomalous. A value of RDEs/RDEt between 2 and 10 represents an anomaly of the second-order, whereas a value of RDEs/RDEt greater than 10 is an anomaly of the first-order. The three-dimensional drainage system is extracted from these images for analysis, and the RDEs and RDEt are calculated, which then indicate the knickpoints. However, each feature in the drainage network resulting from the Stream to Feature tool represents only one drainage stretch. Therefore, one must unite all of the stretches in each of the drainage lines so that they may be recognized as a single feature extending from the spring to the mouth. For this process, as there is specific algorithm called River Merge. Each drainage stretch resulting from the tool Stream to Feature is a feature that has a starting node (from node) and an arrival node (to node), plus a length given in meters. The objective of River Merge is to unite the features such that the arrival node of one stretch coincides with the starting node of the next and, if there are several features with coincident arrival nodes, the union will be made to the stretch with the longest length. River Merge contains a primary loop that continues to run until all the features are ready for the final union.

Simultaneously, a second loop runs analyses of all the features one by one, looking for additional features with nodes coinciding with previous ones. If there is another feature with an arrival node that coincides with the starting node of the feature being analyzed in the second loop. If the feature is not put on hold, the program searches for other features that have arrival nodes coincident with the arrival node of the feature under consideration (convergent drainage stretches), and if these others are not pending and none of them has a length greater than the feature under consideration, the program looks for the feature that has a starting node coincident with the starting node of the feature under consideration (continuation of the drainage stretch in focus) and links this with the feature under consideration in the same "union group". Afterwards, it is executed a routine Dissolve. This tool brings together all of the features within each union group, resulting in a virtual drainage network in which each feature represents a river from its source to its mouth drainage

After the uniting of the drainage stretches, a tool transforms the 2D lines of the network into 3D lines by adding the elevation values (Z), obtained from the image containing the elevation data. Finally, the RDE indexes are calculated. There is a loop for this process that analyzes the longitudinal profiles of all of the rivers one by one. First the RDEt of the river in question is calculated using the relationship RDEt=drop between source and mouth/natural logarithm relative to the total length of the river. A nested loop then analyzes all of the river nodes, measuring the drop since the last RDEs measurement, and when this value exceeds the elevation equidistance provided by the user, the program calculates new RDEs. If the RDEs is at least ten times greater than the RDEt, the program designates a first-order knickpoint; if the RDEs is two to ten times greater than the RDEt, the program designates a second-order knickpoint. Each point created, in addition to the X and Y coordinates and the degree of abnormality, also stores the RDEs, RDEt and RDEs/ RDEt values of the stretch. The lower the value of the elevation equidistance provided by the user, the greater the amount of data in the results. Therefore, the final result of Knickpoint

Finder is a network of points of variable density, depending on the value chosen for the work scale. The values of the indexes RDE between 2 and 10 represent second-order anomalies and the values higher than 10, first-order anomalies.

The RDE index for a segment for a segment can be calculated as follows :

$$RDEs = \left(\frac{\Delta H}{\Delta L}\right)L \tag{1}$$

where:

ΔH: altimetric difference between two extremities of a river segment;

ΔL: extension of the segment;

L: distance between the lower extremity and the river spring.

The RDE total variant (RDEt), which refers to the total extension of a river, takes into account the total declivity between the spring and the mouth of the river, and the natural logarithm of all its extension (Seeber & Gornitz, 1983; Etchebehere et al., 2006; Salomuni et al., 2013).

$$RDEt = \left(\frac{\Delta H}{\Delta L}\right) \tag{2}$$

The flow chart with the main phases executed by the script Knickpoint Finder is demonstrated in the figure 8.

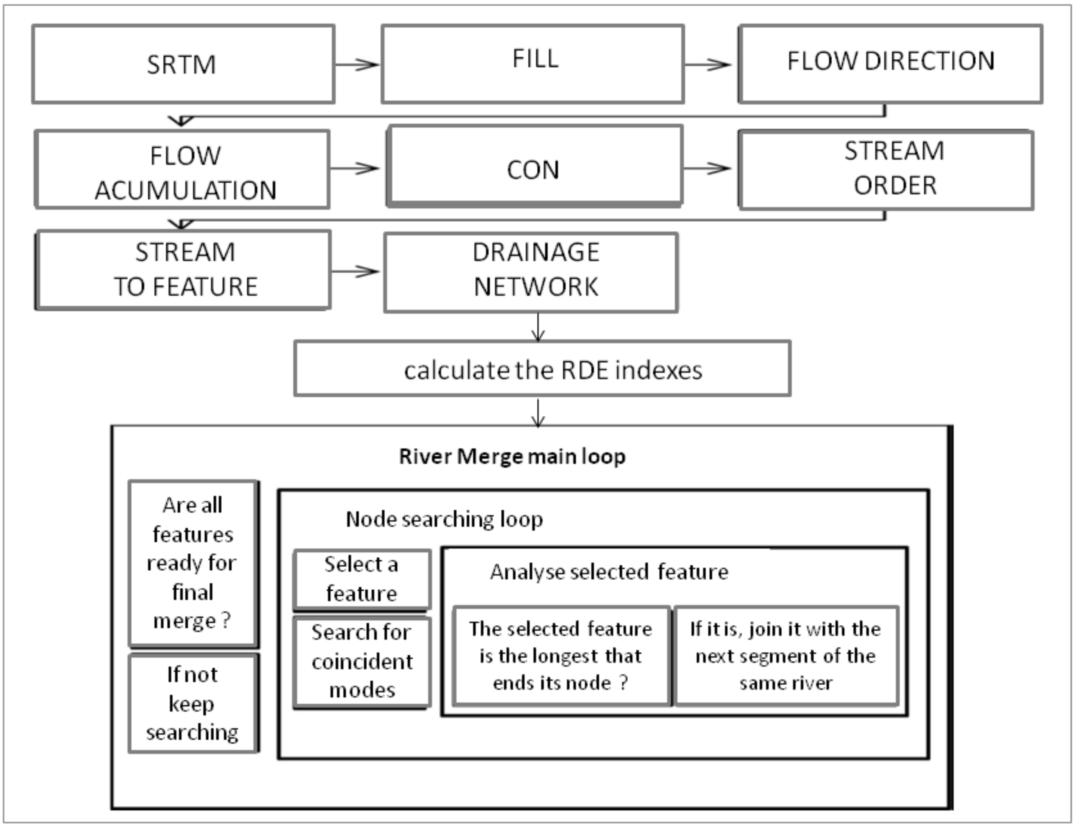



Figure 8 – Flow chart with the main stages executed by the script Knickpoint Finder. Adapted from Queiroz et al. (2015).

# 4. RESULTS

## 4.1 Results of the automatic determination of the hydrography.

The hydrography of the Mirim Lagoon Basin was obtained in different levels of detailment, due to the application of thesholds in the processing, is shown in the figure 9. The thresholds used were: 100 (a), 250 (b), 500 (c) and 1000 (d). The higher the threshold, the more generalized is the hydrography.

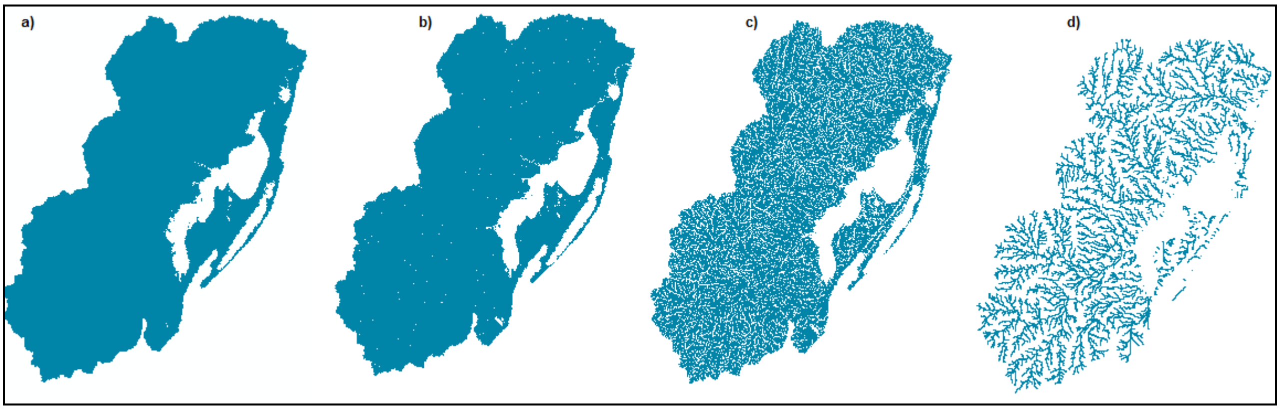



Figure 9 – The Mirim Lagoon Basin Hydrography, with different thresholds used in the processing: a) 100, b) 250 c) 500 and d) 1000.

In the figure 10 are presented the resulting hydrographies for the thresholds 1000 (a), 250 (b), 500 (c) and 100 (d) in a micro-basin , where the presenting scales permit the visualization of differences in the obtained hydrography, with the use o different thresholds.

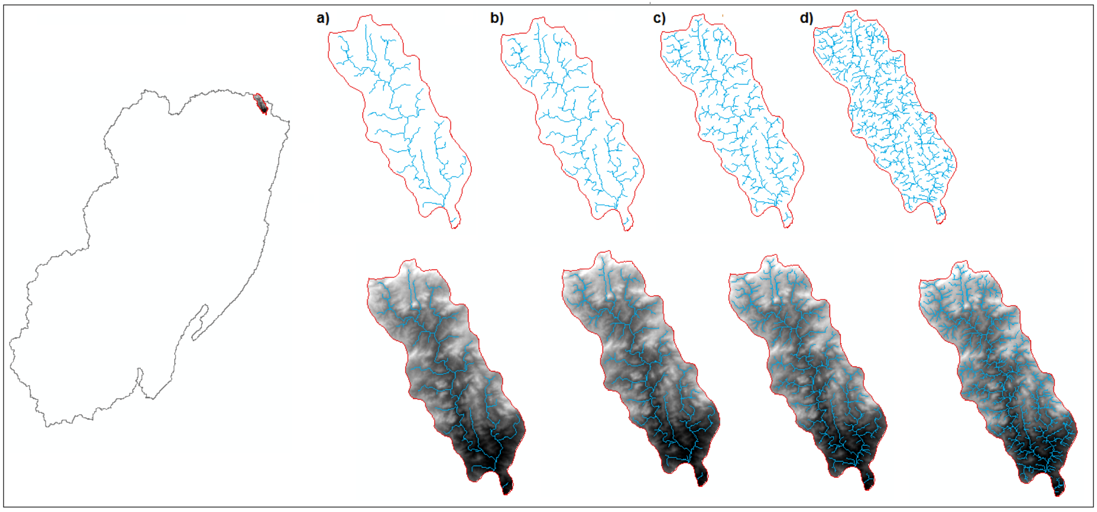



Figure 10 – Hydrography of the micro-basin, with different thresholds applied to the processing: a) 1000, b) 500 c) 250 e d) 100.

The main phases for the determination of the hidrography are:

a) DEM SRTM Non-Void Filled;

b) SRTM Void Filled

c) Flow Direction;

d) Flow Accumulation;

d) Stream to Feature;

e) Strahler's stream orders.

The main phases for the hydrography determination are ilustrated in the figure 11, with a threshold 1000 due to the scale of representation, resulting in a more generalized hydrography.

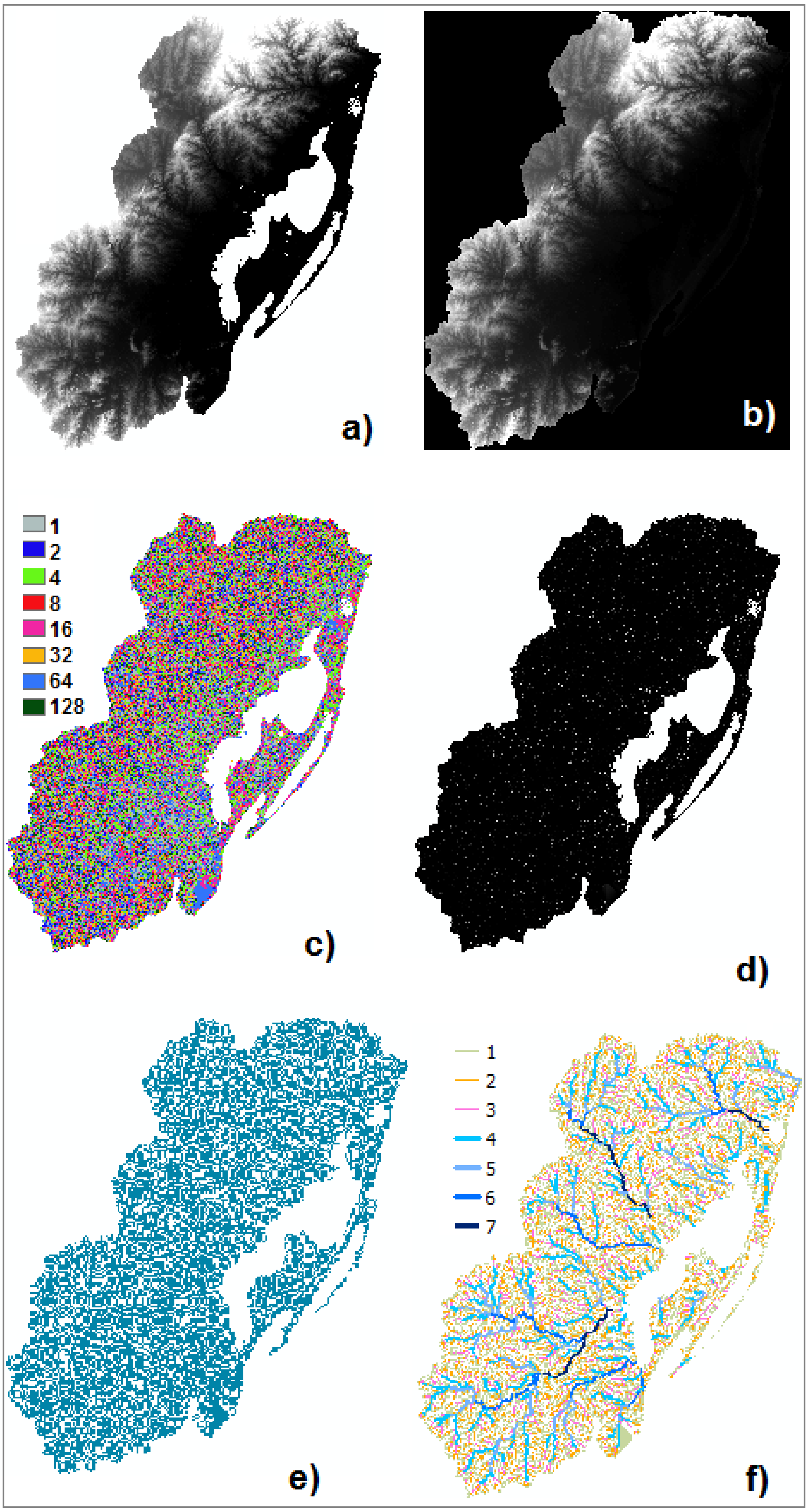



Figure 11 – Main phases of the processing for the obtention of the Hydrography of the Mirim lagoon Basin with a threshold 1000.

4.2 Results of the automatic determination of knickpoints.

A total of 594 knickpoints were obtained with the processing described in the methodology. In the table 2 are presented the RDEt, RDEs and RDEs/RDEt as well as the anomalies of 20 points.

Table 2 – RDEt, RDEs, RDEs/RDEt and anomalies of 20 points in the Basin of Mirim Lagoon Basin.

| FID | Shape * | RDEt | RDEs | RDEsRDEt | Anomaly Order |
|---|---|---|---|---|---|
| 441 | Point | 10.874295 | 2128.402034 | 195.727817 | 1 |
| 92 | Point | 29.790193 | 4540.122375 | 152.403254 | 1 |
| 461 | Point | 16.764099 | 2492.68502 | 148.691858 | 1 |
| 64 | Point | 22.865002 | 2717.120082 | 118.833143 | 1 |
| 305 | Point | 12.674363 | 1432.714004 | 113.040316 | 1 |
| 537 | Point | 8.741258 | 974.790786 | 111.516073 | 1 |
| 159 | Point | 18.040933 | 1896.149263 | 105.102619 | 1 |
| 329 | Point | 23.901933 | 2417.063561 | 101.124186 | 1 |
| 363 | Point | 10.892278 | 1088.373122 | 99.921535 | 1 |
| 481 | Point | 9.271587 | 918.833949 | 99.10212 | 1 |
| 391 | Point | 12.458782 | 1162.397474 | 93.299444 | 1 |
| 81 | Point | 4.74543 | 437.309904 | 92.153896 | 1 |
| 199 | Point | 28.741397 | 2397.820839 | 83.427427 | 1 |
| 93 | Point | 29.790193 | 2482.430386 | 83.330456 | 1 |
| 262 | Point | 17.655457 | 1449.458539 | 82.096912 | 1 |
| 200 | Point | 28.741397 | 2347.966857 | 81.692857 | 1 |
| 95 | Point | 29.790193 | 2428.317026 | 81.513974 | 1 |
| 154 | Point | 10.471793 | 840.921265 | 80.303466 | 1 |
| 448 | Point | 14.953623 | 1199.602664 | 80.221538 | 1 |
| 451 | Point | 14.953623 | 1161.270558 | 77.658139 | 1 |

4.3 Maps with the knickpoints represented.

In the figure 12 is presented the Digital Model of Elevation of the Mirim Lagoon Basin, in gray shades, where the altitude varies between 0 and 513 m. A huge amount of knickpoints are concentrated in the region of highest altitude.

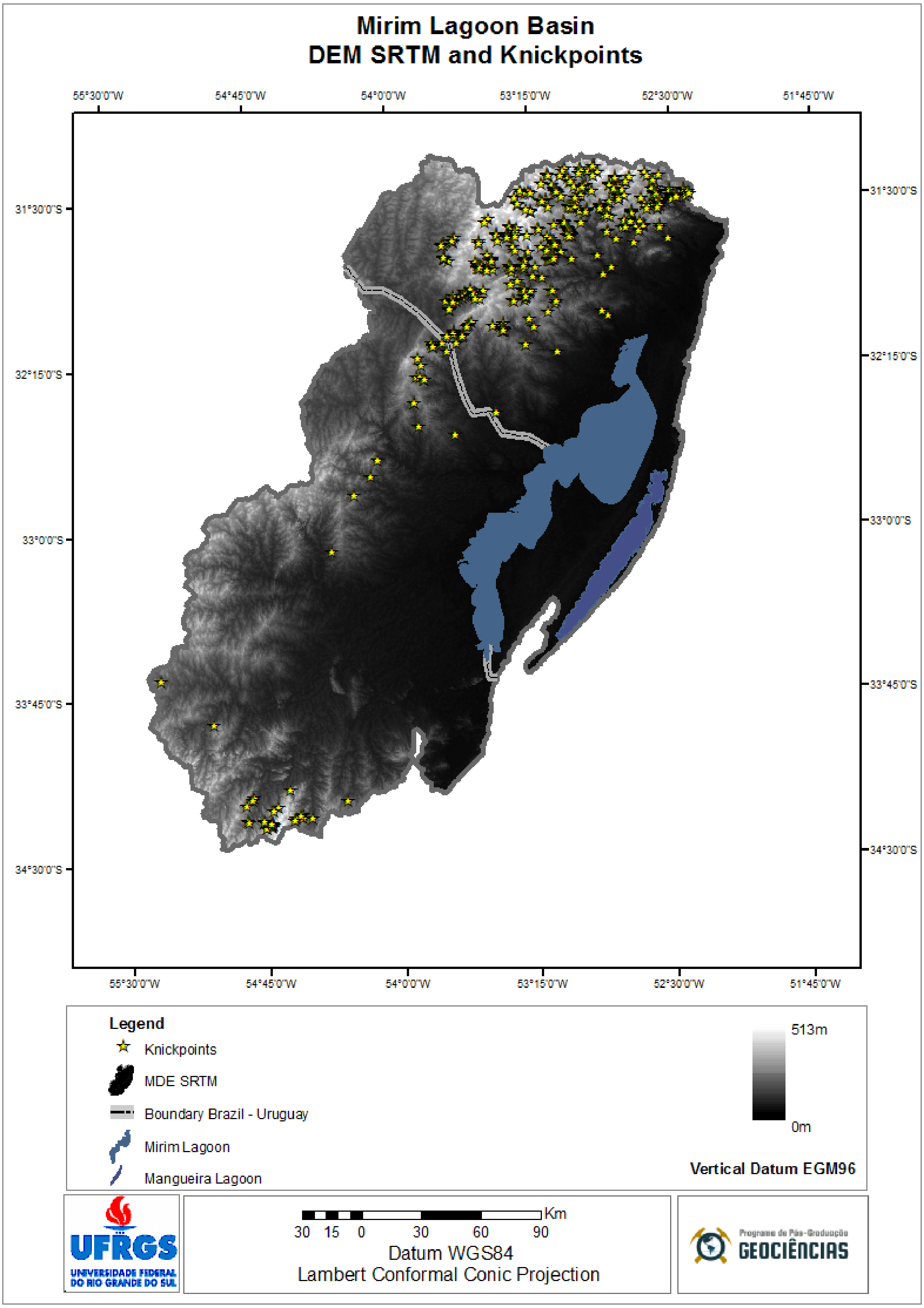



Figure 12 – Digital Model of Elevation (SRTM) and the knickpoints distribution in the Mirim Lagoon Basin Hydrographic Basin.

The figure 13 presents a color digital model of elevation in the Mirim Lagoon Basin and the concentration of knickpoints in the north and northeast portion of the basin.

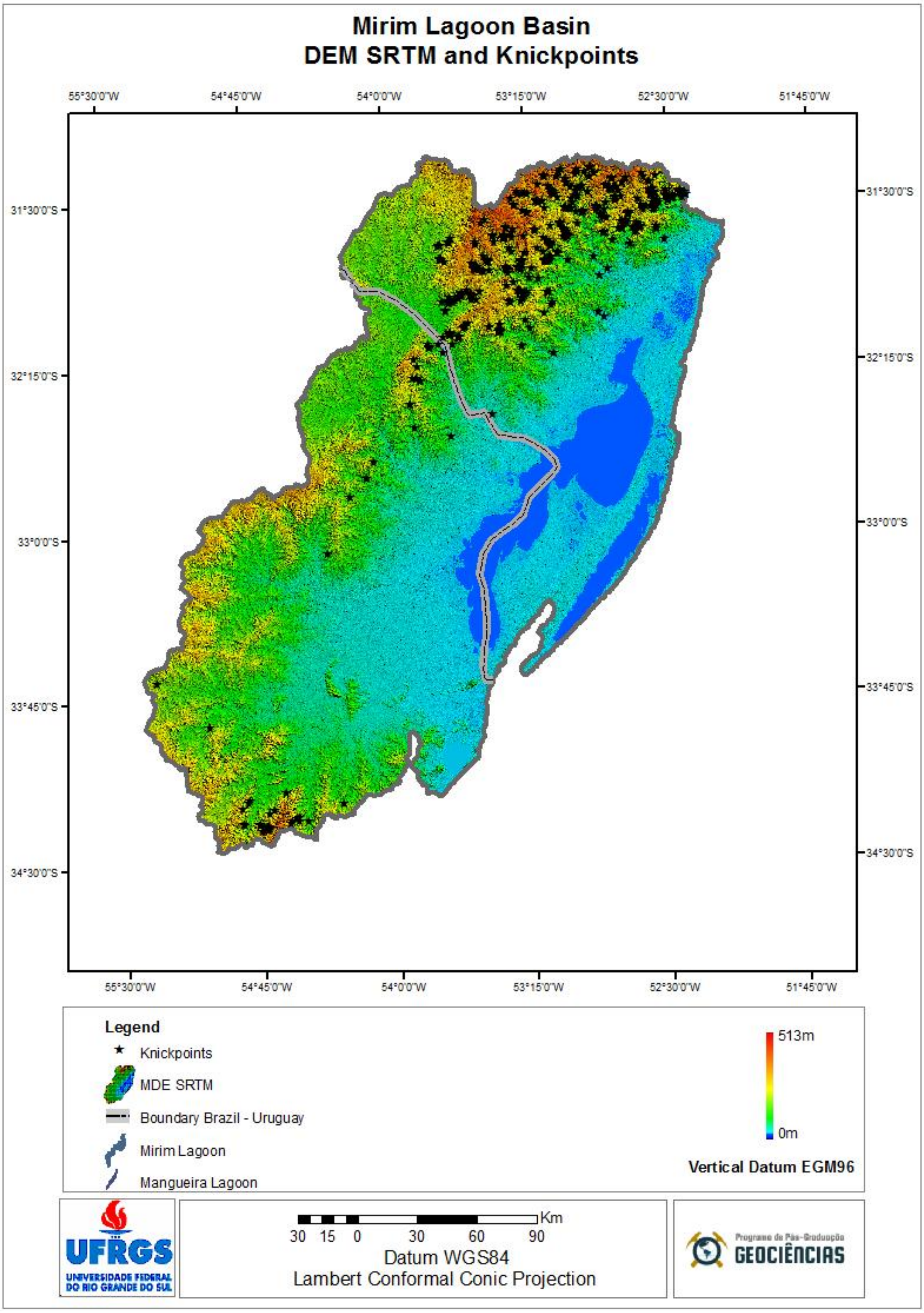



Figure 13 – Digital Model of Elevation (SRTM) and the knickpoints distribution in the Mirim Lagoon Hydrographic Basin.

The figure 14 presents the hypsometric map of the Mirim Lagoon Basin where the knickpoints are located in the highest region altitude, which varies from 0 to 513 m.

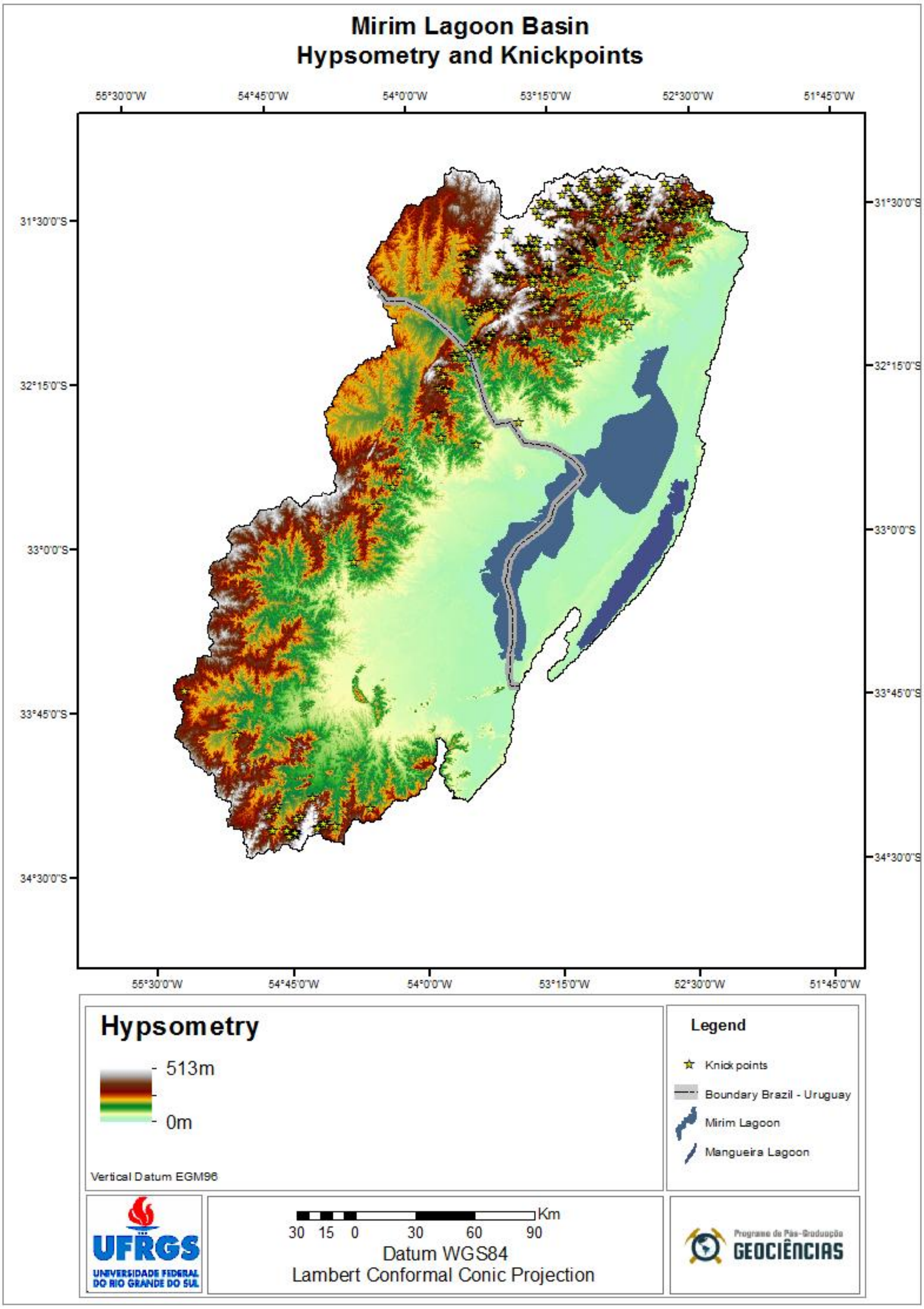



Figure 14 – Hipsometry and knickpoints of the Mirim Lagoon Hydrographic Basin.

The figure 15 presents the declivity map of the Mirim Lagoon Hydrogrphic Basin. The declivity varies between 0 and 45%, predominating values lower than 8%. The predominant relief can be classified as plain to slightly waved.

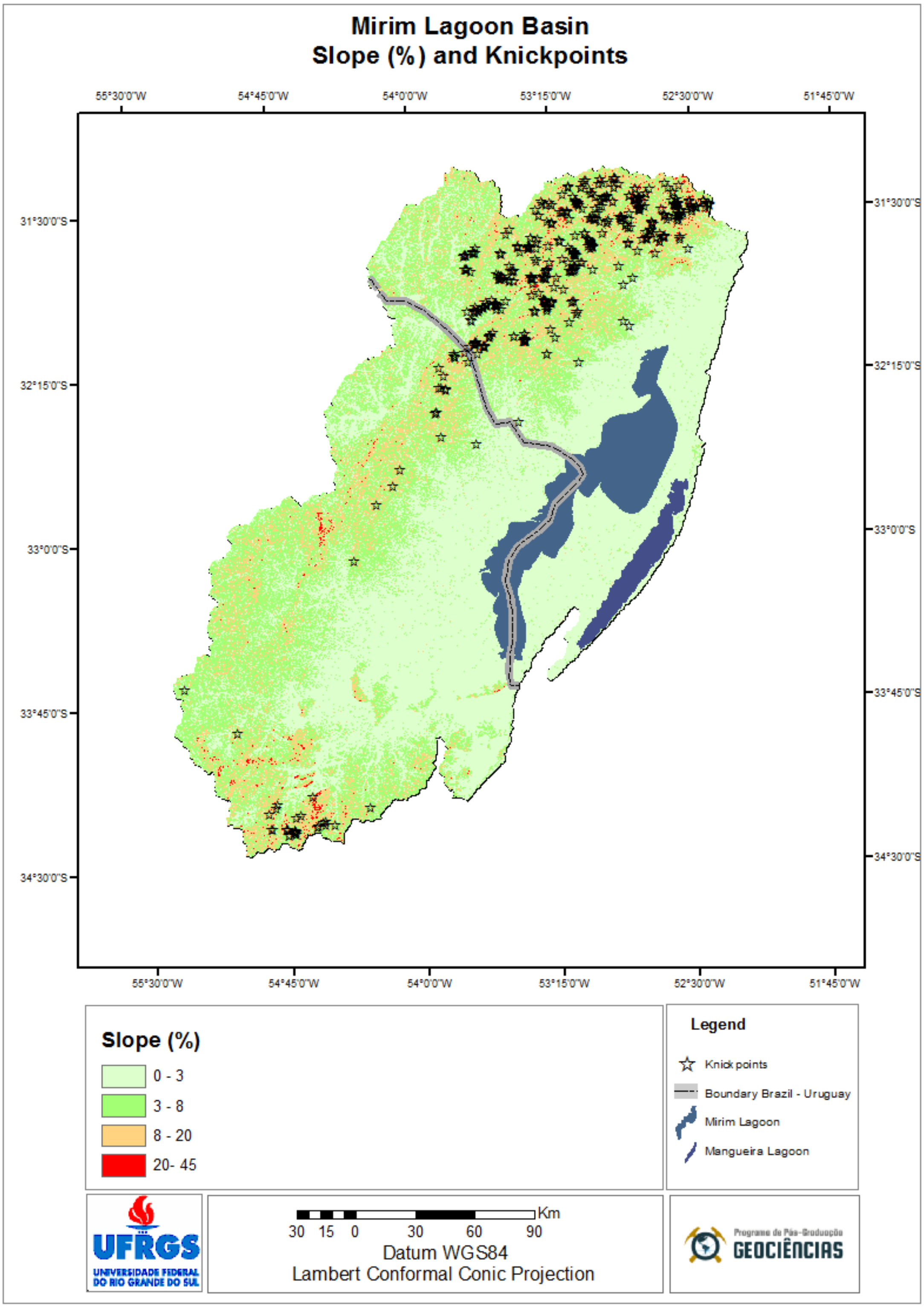



Figure 15 – Declivity map of the Mirim Lagoon Hydrographic Basin.

In the figure 16 is presented a hillshade relief map with the knickpoints, and in the figure 17 the sobreposition of dykes (CPRM, 2008) in the region with the highest concentration of knickpoints.

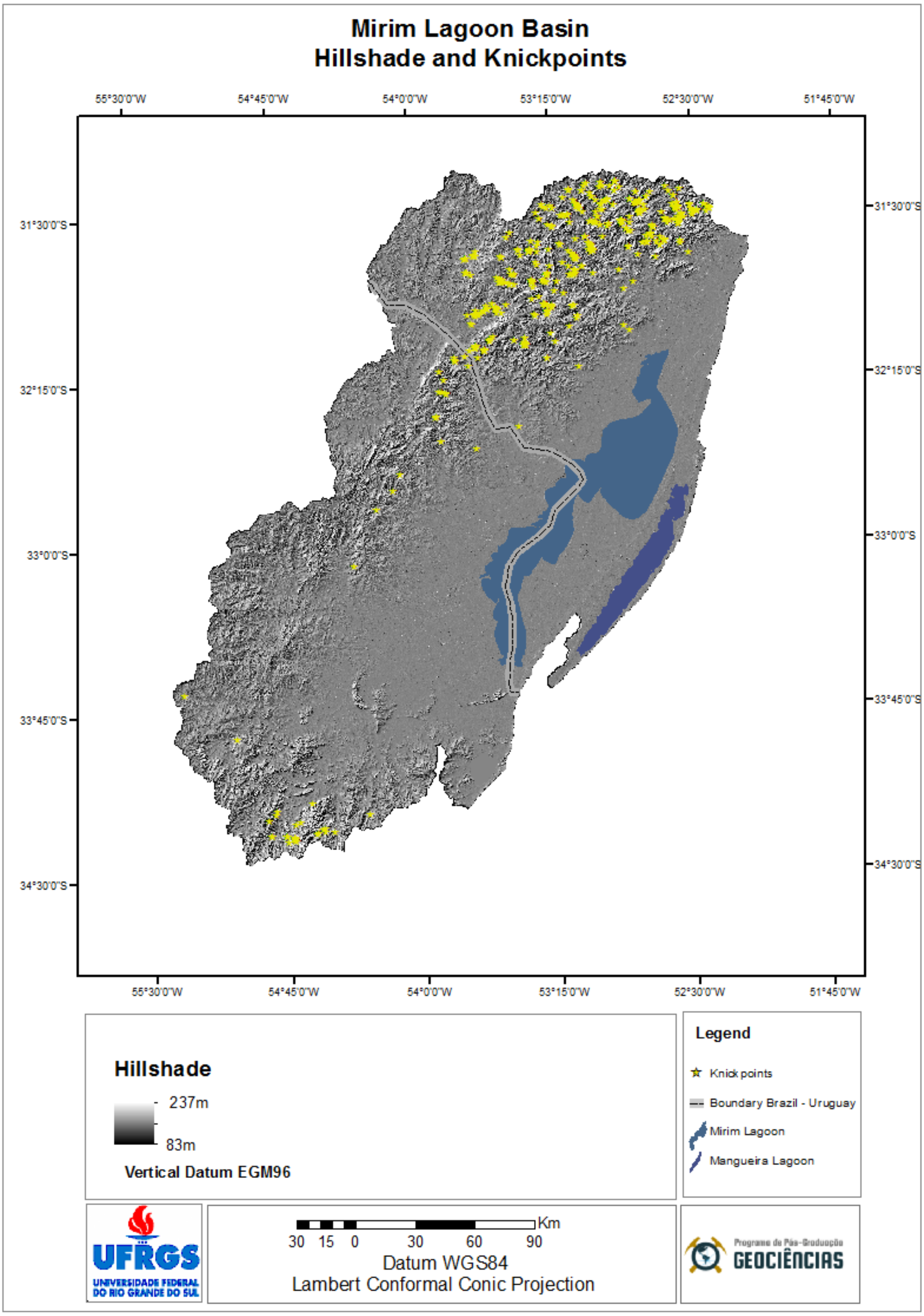



Figure 16 – Hillshade relief of the Mirim Lagoon Hydrographic Basin.

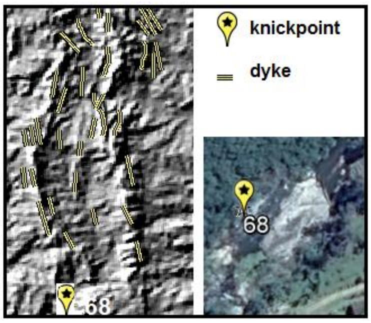



Figure 17 – Dykes (CPRM, 2008), knickpoints and hillshade relief.

The figure 18 presents the Mirim Lagoon Hydrography, with the knickpoints concentrated in the Piratini and Jaguarão sub-basins.

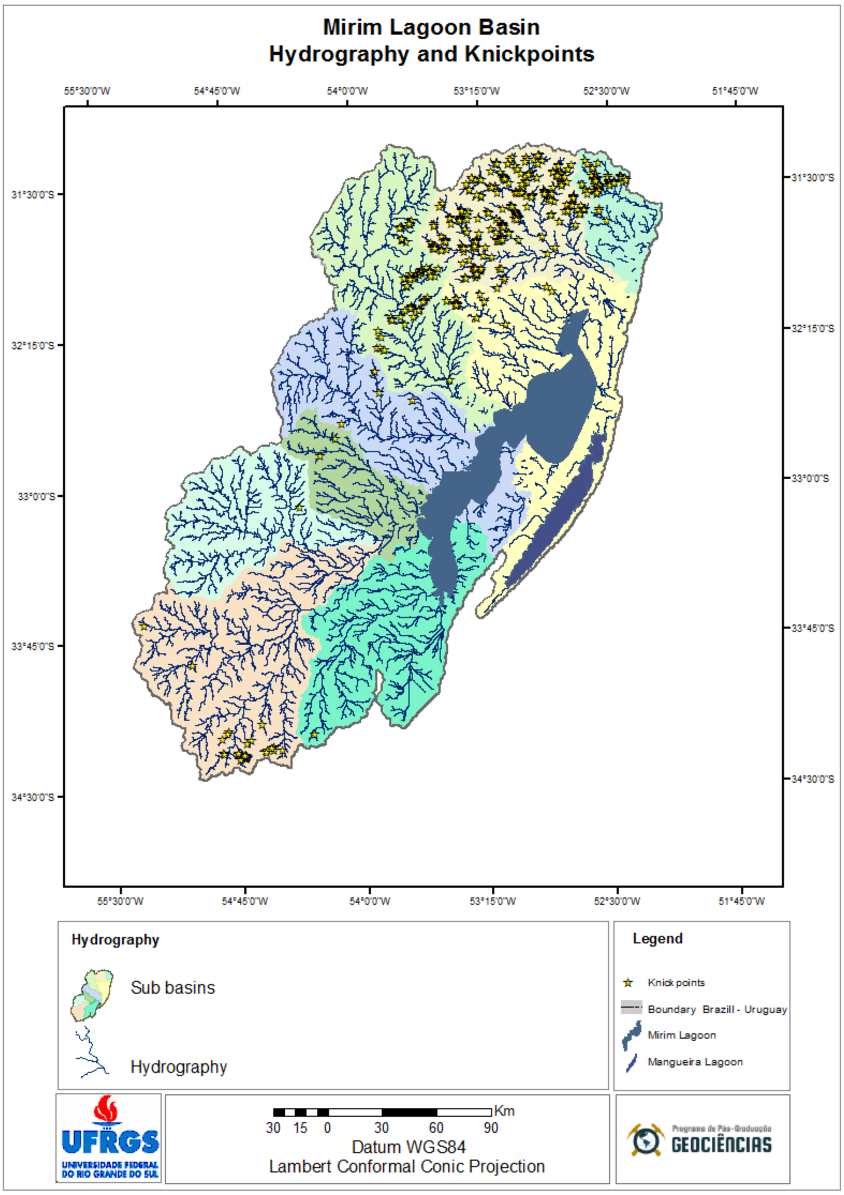



Figure 18 – Hidrography of the Mirim Lagoon and the knickpoints distribution.

In the figure 19 is presented the geologic map of the Mirim Lagoon Basin, with Cenozoic deposits, Gondwana deposits and precambriam basement. The highest concentration of knickpoints is in the precambriam basement.

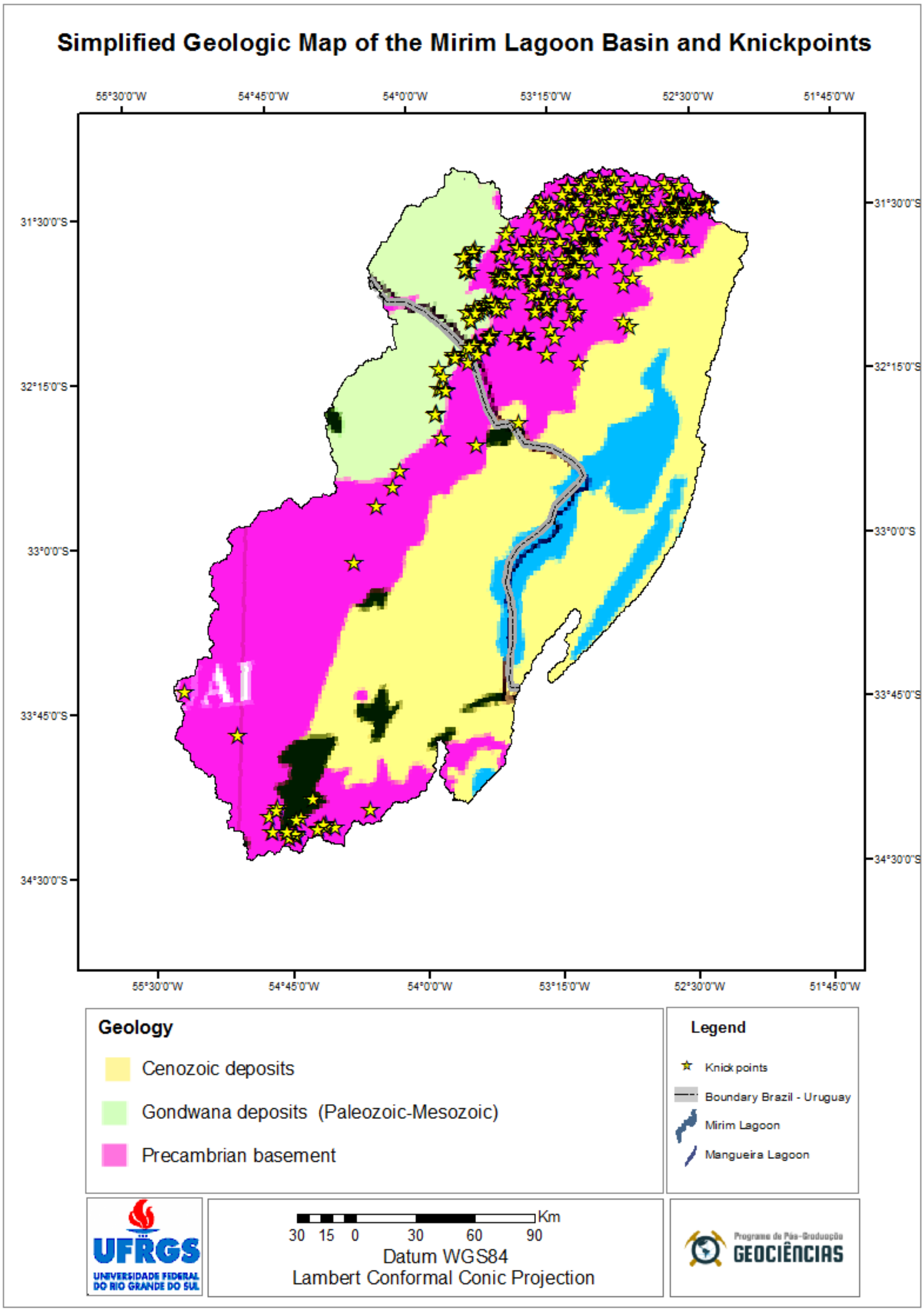



Figure 19 – Simplified geologic map and distribution of knickpoints in the Mirim Lagoon Hydrographic Basin (Adapted from Rosa, 2009)

The figure 20 presents the geology of the Mirim Lagoon Basin with overlain knickpoints, where the highest concentration is in the Neoproterozoic, with rocks of medium to high degrees of metamorphism. The Mirim Lagoon Basin also presents sedimentary rocks (Quaternary and Cretaceous), acids to intermediary (Cambrian–Ordovician), metamorphic of low to middle degree (Mesoproterozoic), middle to high metamorphism (Meso to Neoproterozoic) and volcano-sedimentary (Permian).

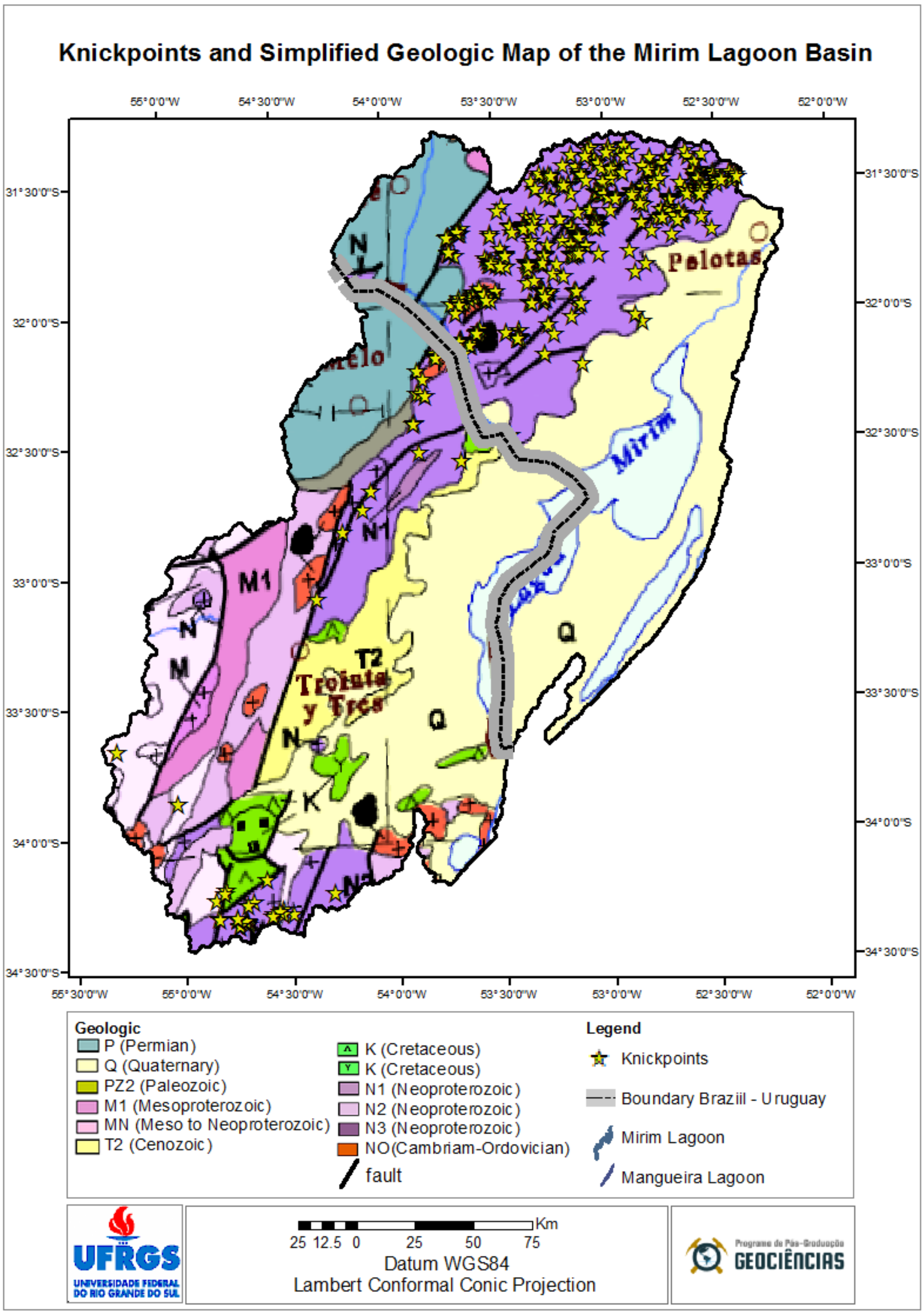



Figure 20 – Simplified geologic map and distribution of knickpoints in the Mirim Lagoon Hydrographic Basin (Adapted from CPRM, 2000 and CPRM, 2017).

In the figure 21 is represented the knickpoints determined in this work, in the region of highest concentration, in a simplified tectonic map with highest detail. The knickpoints are located in the Mantiqueira Province, Pelotas Dominium. According to Rosa (2009), the analysis comparing the magnetic fields patterns with the structures present in Pinheiro Machado defined three magnetic alignment patterns, the first with E-W and N70° E orientation and dips of 30° to 70° S/SE corresponding to the exposition of older granitoids, being identified in the field through measurements in gneisses. In the southeast of Pinheiro Machado, was identified a pattern that occurs as a series of magnetic axes with E-W orientation interpreted as intrusions in a fracture system. This system would represent deep fractures created and/or reactivated in the Tectono-Magmatic South Atlantic Event, which originated the Pelotas Basin. Such anomalies were designated as a structural feature denominated Jaguarão Ligneament (JL). The JL has the same orientation of the Chui Fracture Zone, near to the Brazil-Uruguay border, and magnetic alignments identified in the submerse portion of the Pelotas Basin.

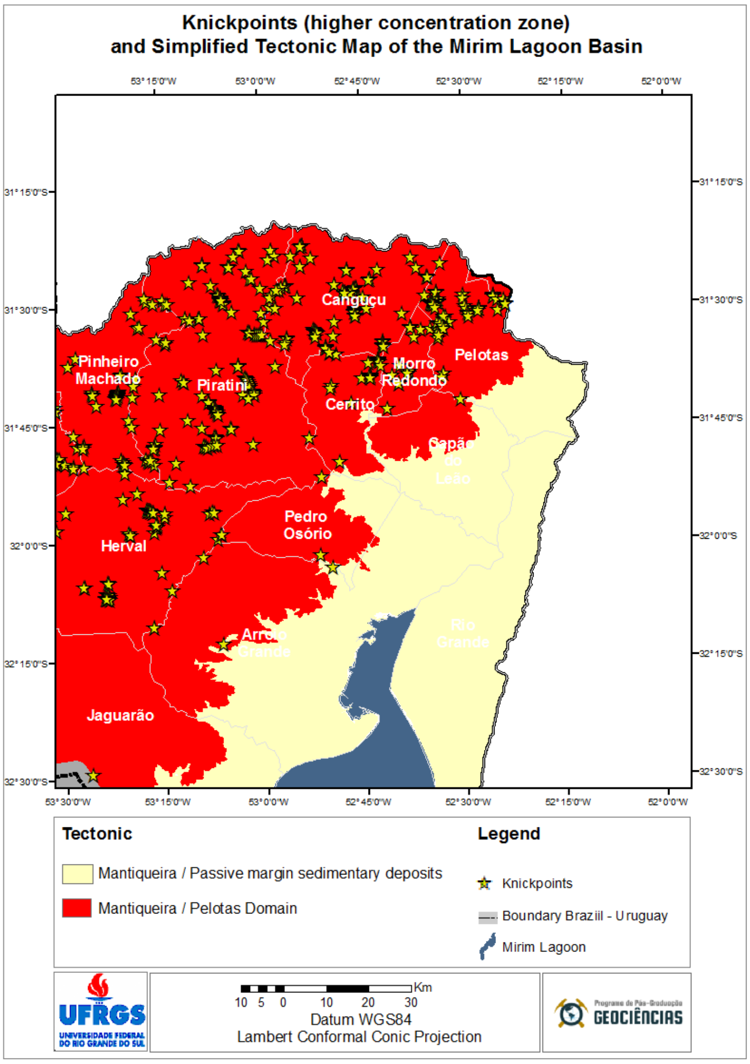



Figure 21 – Region with highest concentration of knickpoints in the Mirim Lagoon Hidrographic Basin and simplified tectonic map (modified from CPRM, 2008).

4.4 Examples of knickpoints observed in the Google Earth program.

The figure 22 presents some examples of knickpoints in the Mirim Lagoon Hydrographic Basin and observed in the Google Earth and their respective coordinates in the table 3.

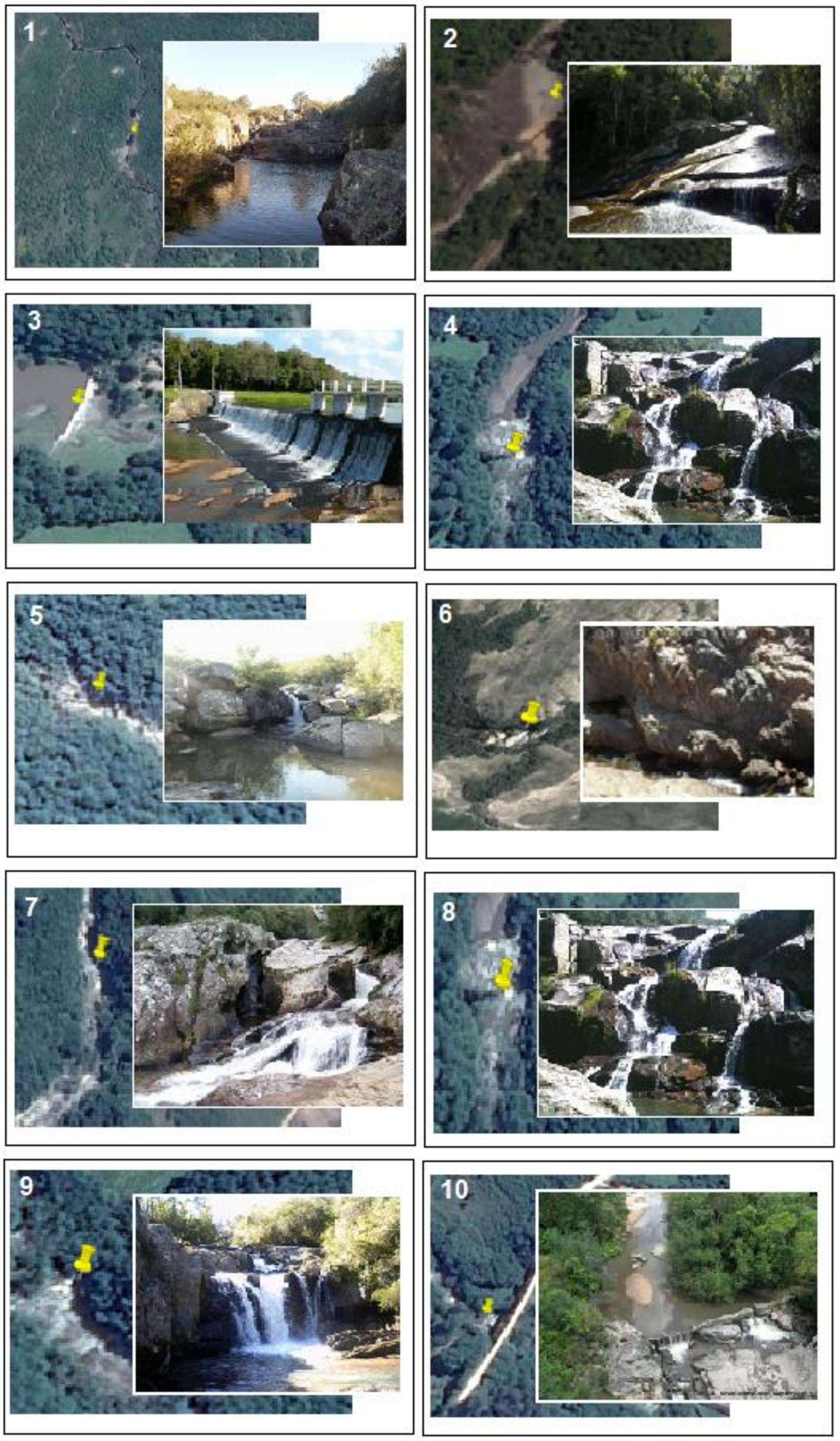



Figure 22 – Examples of knickpoints observed in the Google Earth program.

Table 3– Coordinates of the points of the figure 22.

| Ponto | Latitude ( ° ´ ”) | Longitude ( ° ´ ”) |
|---|---|---|
| 1 | 34°19'51.73"S | 54°42'34.80"W |
| 2 | 31°30'40.66"S | 52°27'36.62"W |
| 3 | 31°31'18.90"S | 52°29'6.16"W |
| 4 | 31°32'56.35"S | 52°37'51.08"W |
| 5 | 32° 6'59.58"S | 53°23'14.33"W |
| 6 | 31°46'51.53"S | 53°42'0.17"W |
| 7 | 31°29'43.43"S | 52°33'39.23"W |
| 8 | 31°32'56.35"S | 52°37'51.08"W |
| 9 | 31°29'55.58"S | 52°34'46.28"W |
| 10 | 31°30'04.65"S | 52°34'33.27"W |

# 5 CONCLUSIONS

In this work the automatic hydrography of the Mirim Lagoon was determined using several thresholds and obtaining different detailment levels and automatically determined 594 knickpoints through the Knickpoint Finder script and the relation declivity-extension.

A digital model of elevation, declivity maps, hillshadowed relief and simplified geologic maps were presented, which permitted the identification of the region with the highest concentration and observe that this concentration occurs mainly in the North and northeast of the basin, in the proximities of their springs, where there is higher amplitude of relief and geologic faults.

The knickpoints distribution in the simplified geologic and tectonic maps shows that there is huge correlation of the results found in this work with the evolution of the region of the Mirim Lagoon Basin and with the geologic faults and dykes in the region of highest concentration of knickpoints.

The drainage evolution is related with the local geology, shaping the relief according to the drainage system orientation.

The automatic techniques of geoprocessing in SIG environment with the use of digital models of SRTM elevation presented in this work are efficient in the determination of both the hydrography and knickpoints in a huge hydrographic basin. These analyses and their representation are of great importance in any hydrologic, environmental and geomorphologic investigation and this study is important for the understanding of the knickpoints distribution in the landscape evolution. Its application demands only SRTM images and a computer with a script for knickpoints determination integrated to the ArcGis program, which defines anomalous sectors of the drainage system and select aims for field investigation, contributing to the improvement of its identification.

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