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Modelagem do *ciclo hidrológico* da Amazônia e suas áreas úmidas

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Modelos hidrológicos e hidráulicos representam os armazenamentos e fluxos do ciclo da água por meio de um conjunto de equações matemáticas. Esses modelos baseados em processos são ferramentas adequadas para entender processos hidrológicos amazônicos, como a troca de água entre rios e planícies de inundação, interações entre águas subterrâneas e superficiais (Miguez-Macho e Fan, 2012; Paiva et al., 2013a) e comportamentos de inundações e secas passadas (Wongchuig et al., 2017). Também são muito úteis para estimar variáveis em regiões sem dados *in situ* (por exemplo, vazão de rios de forma distribuída; Wongchuig et al., 2019) e compreender cenários de alteração hidrológica devido ao desmatamento, regularização de reservatórios e mudanças climáticas (Arias et al., 2020; Guimberteau et al., 2017; Júnior et al., 2015; Lima et al., 2014; Mohor et al., 2015; Pokhrel et al., 2014; Pontes et al., 2019; Sorribas et al., 2016; Zulkafli et al., 2016).

Durante as últimas décadas, muitos modelos foram aplicados na Amazônia em diferentes escalas, desde escala de trecho (ou seja, estudos mais detalhados abordando alguns quilômetros de área de sistemas rio-planície) até toda a escala da bacia. Dados de SR são geralmente adotados como forçantes (por exemplo, chuva), como informações auxiliares para estimar valores de parâmetros (por exemplo, dados topográficos), ou para validação, calibração e assimilação em modelos (por exemplo, vazão e níveis de água do rio). Uma distinção pode ser feita entre (i) modelos hidrológicos que simulam processos verticais como evapotranspiração, infiltração de água no solo e mecanismos de geração de escoamento superficial, e (ii) modelos hidráulicos de águas superficiais, que representam a propagação da vazão ao longo de rios e planícies de inundação, com equações de base física, e permitem a computação de variáveis como elevação e declividade da água superficial, vazão, e extensão e armazenamento de águas superficiais (**Figura 11**).

Mais recentemente, os chamados modelos hidráulicos-hidrológicos foram desenvolvidos para unir os pontos fortes de ambas as abordagens (Fleischmann et al., 2020; Hoch et al., 2016; Paiva et al., 2013a) que existem casos em que esquemas simplificados de inundação estão representados dentro de modelos hidrológicos para estimar a dinâmica de inundação de áreas úmidas. A **Tabela 6** resume as diferenças entre as duas abordagens.

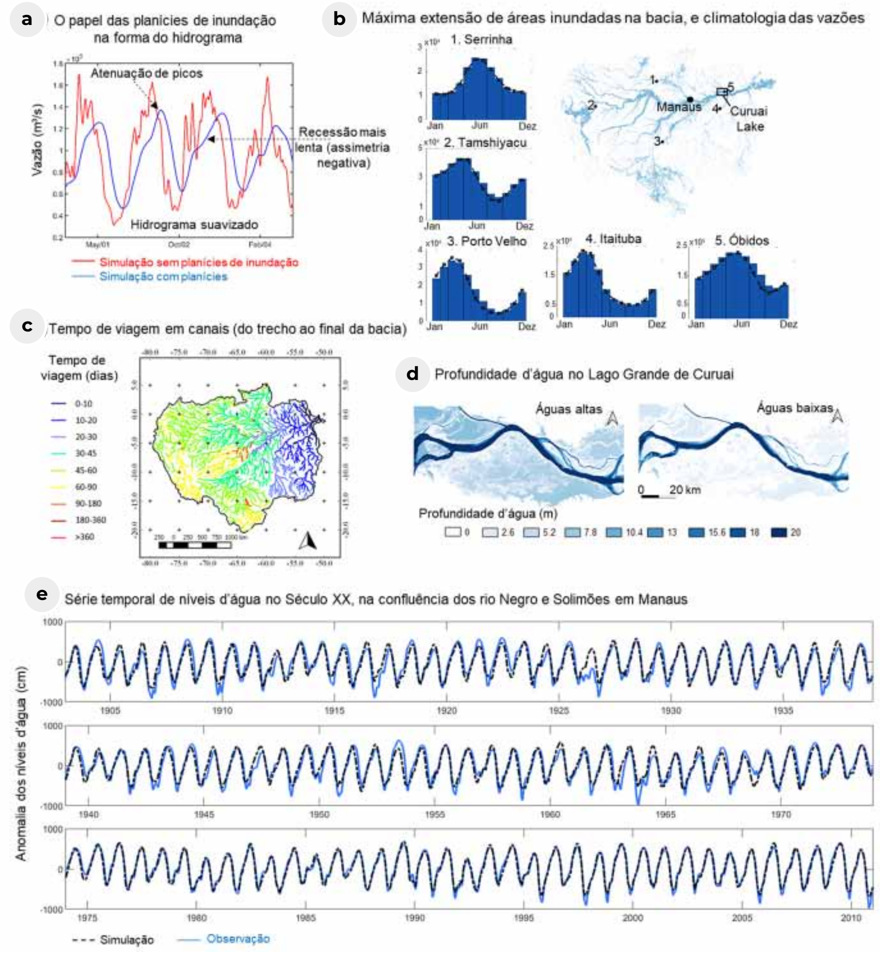

Figura 11: Aplicações recentes de modelos hidrológicos e hidráulicos na bacia Amazônica adicionaram novas perspectivas sobre (a) o papel das planícies de inundação fluviais na forma do hidrograma (Fleischmann et al., 2016), (b) estimativa de vazões de longo prazo (Paiva et al., 2013a), (c) estimativa de tempos de viagem da água (Sorribas et al., 2020), e forneceu a estimativa de (b) climatologia da vazão de longo prazo (Paiva et al., 2013a), (d) profundidades de água de planícies de inundação (exemplo para o Lago Grande de Curuai, temporadas de alta e baixa água de 2014; Rudorff et al., 2014a) e (e) geração de séries temporais de longo prazo de níveis de água (exemplo para a localização de Manaus; Wongchuig et al., 2019).

A primeira geração de modelos na Amazônia envolveu o desenvolvimento de modelos hidrológicos de larga escala, começando pelos estudos de Vörösmarty et al. (1989), Costa e Foley (1997) e Coe et al. (2002). Com o advento dos conjuntos de dados de SR e maior capacidade computacional, diversos modelos foram desenvolvidos, melhorando a representação física dos processos hidrológicos, aumentando a resolução espacial do modelo e passando de estimativas mensais para diárias (Beighley et al., 2009; Coe et al., 2008; Luo et al., 2017; Miguez-Macho e Fan, 2012; Paiva et al., 2013a). Esses modelos geralmente adotam os seguintes dados de entrada baseados em SR: precipitação com o produto TMPA (Collischonn et al., 2008; Getirana et al., 2012; Zubieta et al., 2015), e mais recentemente GPM-IMERG (Zubieta et al., 2017) e MSWEP (Beck et al., 2017a); propriedades da paisagem que incluem comprimentos de terreno e encostas, baseadas em MDEs (a maioria dos estudos usando o SRTM); e mapas de uso da terra e vegetação (mapas globais como os da FAO, ou regionais como os mapas de solo do projeto brasileiro RadamBrasil). Os conjuntos de dados de validação mais comuns oriundos de SR são

TABELA 6
Resumo das principais diferenças entre modelos hidrológicos e hidráulicos de águas superficiais, com exemplos de aplicações de modelos na bacia Amazônica. Alguns exemplos são apresentados em ambas as categorias, uma vez que se referem a modelos hidrológico-hidráulicos.

	MODELOS HIDROLÓGICOS	**MODELOS HIDRÁULICOS DE ÁGUAS SUPERFICIAIS**
Processo principal simulado	Processos verticais (por exemplo, evapotranspiração, infiltração de água no solo e geração de escoamento superficial) e dinâmica das águas subterrâneas.	Interação entre rios e planícies de inundação (por exemplo, armazenamento em planície de inundação, efeitos de remanso).
Forçante principal (condições de contorno)	Precipitação (chuva).	Vazão, nível da água do rio e precipitação.
Principais variáveis de saída	Balanço hídrico, evapotranspiração, armazenamento de água no solo e águas subterrâneas, vazões.	Áreas inundadas, profundidades das águas das planícies de inundação, perfis longitudinais do nível da água em rios, vazões.
Resultados típicos	Quantificação dos componentes do balanço hídrico, divisão de armazenamento de água entre reservatórios superficiais e subterrâneos, dinâmica de evapotranspiração, impactos da ação humana nos componentes do balanço hídrico (por exemplo, mudanças na partição de precipitação em ET e escoamento)	Armazenamento de água nas planícies de inundação e tempo de residência, tempo de viagem da água através dos sistemas de planícies de inundação, curvas-chave (relações entre nível da água e vazão) para uso operacional, impactos da ação humana na dinâmica das inundações.
Exemplos de estudos	Beighley et al. (2009); Coe et al. (2002); Costa e Foley (1997); Cuartas et al. (2012); Miguez-Macho e Fan (2012); Paiva et al. (2013c); Vörösmarty et al. (1989).	Fleischmann et al. (2020); Garambois et al. (2017); Getirana et al. (2012); Miguez-Macho e Fan (2012); Paiva et al. (2013a); Paris et al. (2016); Pinel et al. (2019); Rudorff et al. (2014b); Sorribas et al. (2020); Trigg et al. (2009); Wilson et al. (2007); Yamazaki et al. (2012b).

o nível da água da altimetria por satélite (capítulo 4), extensão de água superficial (capítulo 5) e armazenamento total de água (capítulo 8).

Essas aplicações de modelos aprofundaram nossa compreensão da partição da água entre o solo, água superficial e água subterrânea, e atuaram como laboratórios para melhorar modelos hidrológicos globais, que por sua vez são elementos fundamentais dos modelos do Sistema Terrestre. A avaliação da superfície terrestre e dos modelos hidrológicos e hidrodinâmicos globais na Amazônia tem sido um procedimento padrão no desenvolvimento de modelos e em projetos de intercomparação de modelos (Alkama et al., 2010; Decharme et al., 2008; Getirana et al., 2017b, 2014, 2012; Guimberteau et al., 2017, 2014; Pilotto et al., 2015; Towner et al., 2019; Yamazaki et al., 2011, 2012a; Zulkafli et al., 2013). Em escala da bacia, a fração do armazenamento total de água correspondente às águas superficiais foi estimada em 56%, 41% e 27% por Paiva et al. (2013a), Getirana et al. (2017) e Pokhrel et al. (2013), respectivamente. Esses valores foram comparados com as estimativas baseadas em SR (Frappart et al., 2019, 2012; Papa et al., 2013). Além disso, a *ET* média em escala de bacia foi estimada em 2,39 a 3,26 mm dia-1 por um conjunto de modelos (Getirana et al., 2014), e em 2,72 mm dia-1 por (Paiva et al., 2013a), o que é ligeiramente inferior aos valores em escala de bacia usando SR (Paca et al., 2019) e uma rede *in situ* de torres de fluxo (método de covariância de vórtices turbulentos; Costa et al. (2010), que estimou valores de 3,11 a 3,58 mm dia-1 através de um gradiente que vai do sul da floresta Amazônica até a floresta úmida equatorial. O papel do armazenamento de água do solo para sustentar a *ET* da estação seca na Amazônia foi mostrado por experimentos de modelagem em escala local (Fang et al., 2017) e de bacia (Getirana et al., 2014). Alguns estudos abordaram o papel das águas subterrâneas e do armazenamento do solo no balanço hídrico, e a importância de sua representação em modelos hidrológicos. As aplicações nas áreas de cabeceira mostraram o predomínio das águas subterrâneas no armazenamento de água (Cuartas et al., 2012; Niu et al., 2017), de acordo com estudos de monitoramento in situ (Hodnett et al., 1997). Miguez-Macho e Fan (2012) sugeriram o mesmo padrão em toda a bacia. O modelo deles também indicou uma importante retroalimentação em duas vias entre as áreas inundadas e as águas subterrâneas, e a existência de grandes áreas não sujeitas a inundações superficiais em toda a bacia onde um alto nível de lençol freático seria responsável por manter o alto teor de água do solo durante todo o ano. A simulação de múltiplas camadas de solo no modelo de superfície terrestre ORCHIDEE, em contraste com modelos simples do tipo *bucket* (“balde”) de duas camadas, também foi demonstrada para melhorar a representação da dinâmica da água do solo e do armazenamento total de água na Amazônia, especialmente para as regiões mais secas nas sub-bacias do sul (Guimberteau et al., 2014).

Entre os modelos hidráulicos de águas superficiais, o estudo pioneiro de Wilson et al. (2007) é um dos primeiros experimentos de modelagem hidráulica realizado em grandes domínios, o que, mais tarde, levou ao desenvolvimento de muitas aplicações globais de modelos hidrodinâmicos (Bates et al., 2018). Os autores aplicaram o modelo LISFLOOD-FP em um trecho de 260 km do rio Solimões, e estimaram a troca de água rio-planície em pelo menos 40% do volume do rio nesse trecho. Para um trecho relativamente diferente na Amazônia Central (de São Paulo de Olivença a Óbidos), Richey et al. (1989) estimaram essa proporção em 30% com base em um método de propagação mais simples, enquanto Sorribas et al. (2020) estimaram um valor de 40% para o sistema amazônico, com base em modelagem hidráulica em larga escala (veja abaixo). Os autores também constataram que a acurácia do modelo foi maior para o período de água alta, como também foi relatado por estudos recentes (Pinel et al., 2019; Rudorff et al., 2014b), provavelmente devido à má representação das heterogeneidades do terreno e pequenos lagos desconectados durante a estação seca. Ademais, uma vez que a troca de água rio-planície ocorre frequentemente através de canais da planície de inundação e diques rompidos, que dificultam sua conceituação como umas simples área de transbordamento do canal fluvial (Trigg et al., 2012), os modelos hidráulicos têm o desafio de estimar parâmetros de canal efetivos que representam esses processos complexos (Fleischmann et al., 2018; Trigg et al., 2009). Esforços recentes vêm abordando esse tema, considerando, por exemplo, a incorporação em modelos de diferentes formas de seção transversal (Neal et al., 2015), bem como a assimilação da altimetria por satélite para inferir a batimetria de canais (Brêda et al., 2019; Garambois et al., 2020; Pujol et al., 2020). Outras aplicações em escala de lagos de várzea foram desenvolvidas por Bonnet et al. (2008, 2017), Ji et al. (2019), Trigg et al. (2009) e Wilson et al. (2007), e abordaram o papel relativo na entrada de água no sistema do escoamento gerado localmente com a vazão proveniente do rio principal. Os estudos abordaram desde sistemas locais dominados pelo escoamento no Lago Calado (Ji et al., 2019; Lesack e Melack, 1995) até os dominados pelo rio nos lagos Lago Grande de Curuai (**Figura 11d**) e Lago Janauacá (Bonnet et al., 2017, 2008; Pinel et al., 2019; Rudorff et al., 2014a, 2014b), através de padrões de fluxo ora canalizados ora difusos. No caso dos lagos Curuai e Janauacá, o rio Solimões-Amazonas foi responsável por 82% e 93% dos fluxos anuais que entram na planície de inundação, respectivamente (Bonnet et al., 2017; Rudorff et al., 2014a).

O primeiro modelo de inundação em escala de bacia foi introduzido por Coe et al. (2002), e inúmeros modelos hidrológicos foram desenvolvidos e acoplados a esquemas de inundação posteriormente (Coe et al., 2008; Getirana et al., 2017b, 2012; Hoch et al., 2016; Luo et al., 2017; Miguez-Macho e Fan, 2012; Paiva et al., 2013a; Yamazaki et al., 2012b, 2011). Os modelos apresentam diferentes graus de representação física, com a simulação de planícies de inundação passando de componentes de armazenamento simples para esquemas hidráulicos dinâmicos, que podem representar processos relevantes como efeitos de remanso.

Para modelos hidráulicos, outras informações baseadas em SR que são necessárias como dados de entrada incluem a geometria do canal do rio, como largura, e topografia de planície de inundação, obtida geralmente por MDEs (principalmente SRTM e seus derivados com remoção de vegetação para representar o terreno descoberto; ver Baugh et al. (2013), O'Loughlin et al. (2016), Yamazaki et al. (2019) e Fassoni-Andrade et al. (2020b)). Para modelos hidráulicos em escala local, a parametrização adicional geralmente envolve a definição de rugosidade da planície de inundação com base em mapas de cobertura da terra (Pinel et al., 2019; Rudorff et al., 2014b). Os conjuntos de dados de validação do SR são tipicamente elevação e extensão de águas superficiais (Hall et al., 2011; Schumann et al., 2009). Essas aplicações de modelos hidráulicos revelaram a combinação de efeitos de remanso e armazenamento de planícies de inundação no processo de propagação de cheias ao longo dos rios amazônicos (Paiva et al., 2013a), causando forte atenuação e atraso de até 2,5 meses. O armazenamento em planícies de inundação também é responsável pela assimetria negativa dos hidrogramas nos principais rios da Amazônia, com uma subida (enchente) mais lenta e uma queda (vazante) mais rápida (Fleischmann et al., 2016; **Figura 11a**). Sorribas et al. (2020) utilizaram métodos de rastreamento de partículas para estimar os tempos de viagem de águas superficiais ao longo da bacia Amazônica em 45 dias (mediana), com 20% das águas do rio Amazonas fluindo através de planícies de inundação (**Figura 11c**).

Embora as aplicações em escala de bacia tenham empregado modelos unidimensionais (direção longitudinal ao longo dos rios), a necessidade de representar o fluxo difuso bidimensional em planícies de inundação, especialmente durante o recuo das águas, foi destacada por Alsdorf et al. (2005), que combinaram dados de interferometria com um modelo simples de continuidade para mostrar que o armazenamento em planícies de inundação diminui com a distância do canal principal. Geralmente, o nível da água no sistema rio-planície não é completamente horizontal, e o rio-planície não é homogeneamente misturado (Alsdorf et al., 2007), como assumido por vários modelos unidimensionais. Enquanto uma caracterização adequada das complexas interações rio-planície com modelos hidráulicos tem sido feita em escalas locais (Pinel et al., 2019; Rudorff et al., 2014b), isto ainda está para ser desenvolvido para a escala regional – por exemplo, a habilidade de inferir padrões em altíssima resolução (por exemplo, resolução espacial de 30 metros), para toda a Amazônia central, com resolução semanal a mensal. Finalmente, o acoplamento completo entre modelos hidrológicos e hidráulicos tem sido sugerido para melhorar a representação das interações da área inundável com a terra firme, por exemplo, por meio de uma representação mais adequada da evaporação em águas abertas em áreas inundadas (Getirana et al., 2017a). Entretanto, estudos recentes sugerem que este processo tem um impacto relativamente baixo sobre as estimativas de evapotranspiração total devido à evapotranspiração ser geralmente limitada por energia (e não por disponibilidade de água) na Amazônia. Espera-se uma conclusão diferente para áreas úmidas semiáridas (Fleischmann et al., 2018).

A validação em escala regional de modelos de inundação foi feita com estimativas de extensão de águas superficiais (Getirana et al., 2012; Luo et al., 2017; Paiva et al., 2013b; Wilson et al., 2007; Yamazaki et al., 2011), com base nos produtos de Hess et al. (2003), GIEMS de Prigent et al. (2007), e mais recentemente com o banco de dados SWAF (Parrens et al., 2017) (ver capítulo 5 para uma descrição desses produtos). Embora o ciclo sazonal de inundação seja geralmente bem capturado pela maioria dos modelos, as estimativas divergem em termos de magnitude (Fleischmann et al., 2020), e a fusão entre diferentes técnicas é provavelmente a solução ideal. No entanto, são necessários experimentos de validação mais detalhados, por exemplo, com mapas baseados em dados SAR, embora muitas classificações de dados SAR já tenham sido desenvolvidas para áreas úmidas individuais da Amazônia (capítulo 5). Um aplicativo recente utilizou imagens ALOS/PALSAR para validação de modelo local no sistema da planície de inundação Janauacá (Pinel et al., 2019).

Em relação ao nível da água, os modelos hidráulicos são tipicamente capazes de representar anomalias de forma satisfatória. As estimativas dos valores absolutos, no entanto, são geralmente menos acuradas (Fleischmann et al., 2019), embora bons resultados tenham sido alcançados (Wilson et al., 2007). As centenas de estações virtuais disponíveis (ver capítulo 7) proporcionaram melhorias revolucionárias nos métodos de modelagem, especialmente em termos de validação de modelos distribuídos com múltiplas estações virtuais (Fleischmann et al., 2020; Getirana et al., 2017b; Paiva et al., 2013a) e calibração e assimilação no modelo (Brêda et al., 2019; Oliveira et al., 2021). Os exercícios de validação produziram coeficientes de Nash-Sutcliffe superiores a 0,6 para 60% das 212 estações virtuais ENVISAT avaliadas por Paiva et al. (2013a), e erros de amplitude inferiores a 0,8 m e viés absoluto inferior a 2,3 m para a maioria das estações analisadas por Yamazaki et al. (2012b). A combinação da altimetria por satélite com um modelo hidráulico para um trecho sem dados *in situ* do rio Xingu levou Garambois et al. (2017) a propor o conceito de visibilidade hidráulica por meio de conjuntos de dados de SR, ou seja, a capacidade dos dados de altimetria por satélite atuais e futuros para estimar corretamente as variáveis hidráulicas do rio. Os dados de altimetria mostraram-se relevantes para a compreensão do funcionamento hidráulico de trechos complexos dos rios amazônicos, especialmente ao longo de trechos com morfologia heterogênea do leito e forte controle a jusante, que têm grandes efeitos no nível da água e na declividade (Birkett et al., 2002).

As principais variáveis de saída que foram abordadas pelos modelos hidrológico-hidráulicos são *ET*, armazenamento de água do solo, vazão, nível da água e extensão de água superficial. No entanto, outras variáveis também são importantes para uma compreensão eficaz do ciclo da água, e precisam ser melhor limitadas dentro dos sistemas de modelagem. Por exemplo, apenas alguns estudos abordaram a velocidade da água simulada (Dias et al., 2011; Fassoni-Andrade, 2020; Pinel et al., 2019) e armazenamento de inundações (Fleischmann et al., 2020; Getirana et al., 2017a; Paiva et al., 2013a) nas áreas úmidas amazônicas, que são variáveis fundamentais para entender a dinâmica das inundações, embora esta última (armazenamento de inundações) já tenha sido estimada por diferentes métodos de SR (ver capítulo 9).

Como ainda há incertezas em ambos os modelos e em estimativas de SR, técnicas de calibração de modelos e assimilação de dados (AD) foram desenvolvidas para melhorar a previsibilidade do modelo, com base na combinação de ambas. A calibração do modelo foi realizada com altimetria por satélite por Getirana et al. (2013) e Oliveira et al. (2021), mostrando os benefícios do uso desses conjuntos de dados para a melhoria geral do modelo em termos de estimativa de vazões. Por sua vez, a avaliação das técnicas de AD (principalmente os métodos baseados em Filtros de Kalman) dentro da Amazônia envolveu muitos experimentos com dados de SR (por exemplo, altimetria por satélite), da escala de trecho de rio à regional (Brêda et al., 2019; Emery et al., 2018; Garambois et al., 2017; Paiva et al., 2013b). Esses estudos mostraram a aplicabilidade desses métodos para melhorar as estimativas do modelo e a representação do ciclo da água em geral. A utilidade dos esquemas de AD para a melhor estimativa de vazões foi demonstrada para previsão (Paiva et al., 2013b), compreensão de eventos extremos passados (Wongchuig et al., 2019) e estimativa da vazão em tempo quase real (Paris et al., 2016). O estudo de Wongchuig et al. (2019) foi o primeiro a estimar vazões de forma espacialmente distribuídas nos últimos 100 anos, estimando eventos extremos de seca e inundação em locais previamente não registrados (**Figura 11e**). Eles seguem um padrão geral de tendência significativa de eventos de seca crescente no sul e eventos de inundação nas regiões oeste e noroeste da Amazônia (Callède et al., 2004; Correa et al., 2017; Espinoza Villar et al., 2009a; Lopes et al., 2016; Molina-Carpio et al., 2017). Além de vazões e níveis da água, outras variáveis estimadas por SR podem também ser usadas por meio da AD e poderiam ser aplicadas na Amazônia, por exemplo, umidade do solo (Baguis e Roulin, 2017; Crowley et al., 2008; Massari et al., 2015), mudança de armazenamento de água terrestre (Khaki et al., 2019, 2018) e extensão de áreas inundadas. Adicionalmente, a futura missão SWOT fornecerá informações inovadoras para a modelagem hidráulica dos rios amazônicos. Muitos estudos têm discutido a utilidade da missão para melhor estimar as variáveis hidráulicas na Amazônia, em escala de trechos de rio (por exemplo, no baixo rio Madeira; Brêda et al., 2019) até a bacia inteira (Emery et al., 2020; Wongchuig et al., 2020). Novas formas de incorporar os níveis da água de altimetria por satélite irão permitir o desenvolvimento da próxima geração de modelos hidráulicos para a Amazônia, visando a uma melhor representação de processos locais, como a heterogeneidade da superfície da água que ocorre devido a controles hidráulicos como reduções de largura de canal (Garambois et al., 2017; Montazem et al., 2019; Pujol et al., 2020).

A maioria das aplicações de modelos em áreas úmidas da Amazônia se concentrou em partes específicas das planícies de inundação da Amazônia central ou em estudos que contemplassem toda a bacia Amazônica. A simulação das planícies de inundação fluviais ainda enfrenta algumas limitações para ser realizada com precisão sobre sistemas fluviais complexos e dinâmicos como nos sopés dos Andes, que estão associados a múltiplos leques aluviais, áreas úmidas desconectadas do rio principal em termos de águas superficiais, mas conectadas através de águas subterrâneas (por exemplo, as florestas de pântanos alimentadas com água subterrânea; Hamilton et al., 2007), e dinâmicas hidrológicas relativamente rápidas, que por sua vez dificultam o monitoramento baseado em SR de variáveis como extensão de inundação e níveis da água. Mais avanços na estimativa da topografia ao longo das áreas úmidas florestadas e canais adjacentes são necessários, bem como técnicas de modelos acoplados de águas subterrâneas e de superfície. Além das planícies de inundação fluviais, existem outros tipos de áreas úmidas na bacia Amazônica, que muitas vezes são denominadas áreas úmidas interfluviais (Junk et al., 2011). Elas combinam processos de inundação endógeno e exógeno em diferentes graus (Bourrel et al., 2009), e estão mais sujeitas a chuvas locais e menos conectados a rios adjacentes (Reis et al., 2019). Estão também associadas a diferentes tipos de vegetação e ecossistemas (por exemplo, campinas, campinaranas e savanas). Embora os modelos hidráulicos unidimensionais tenham se mostrado satisfatórios para simular os processos ao longo das planícies de inundação fluviais (Trigg et al., 2009), as áreas úmidas interfluviais requerem uma simulação bidimensional para capturar adequadamente o fluxo difuso na área úmida. Fleischmann et al. (2020) apresentaram pela primeira vez uma avaliação de um modelo com foco nas áreas úmidas interfluviais do rio Negro, que estão associadas a eventos neotectônicos e ao ambiente de campinas e campinaranas dentro da floresta Amazônica (Rossetti et al., 2017), e, portanto, diferem muito da Amazônia central em termos de inundações, vegetação e características do solo. Belger et al. (2011) utilizaram uma série temporal de imagens Radarsat e medições *in situ* do nível da água e chuva local para estimar mudanças na inundação em uma área úmida da bacia do rio Negro. Os modelos unidimensionais mostraram-se irrealistas para simular a elevação da superfície da água nessas áreas. Estudos futuros devem abordar ainda mais a hidrologia desses sistemas complexos de áreas úmidas interfluviais, incluindo as áreas de *Llanos de Moxos* (Hamilton et al., 2004; Ovando et al., 2018), Roraima (Hamilton et al., 2002) e Peru (Kvist e Nebel, 2001), visando a entender melhor as diferenças hidrológicas entre planícies de inundação e áreas úmidas interfluviais, e ao mesmo tempo ajudando nossa compreensão sobre os diversos ecossistemas amazônicos particulares que dependem deles, bem como as diferenças em termos de conectividade entre rio e áreas úmidas.

A parte a jusante da bacia Amazônica permanece relativamente inexplorada em termos de modelagem hidráulica e SR. Isso pode ser explicado pela dinâmica complexa do estuário, que é influenciado por uma ampla gama de escalas de tempo, desde as marés com variações intra-diárias que se propagam rio acima a partir do Oceano Atlântico, através do delta da Amazônia, até as escalas de tempo sazonais e interanuais conduzidas pela hidrologia da bacia. Além disso, os efeitos das marés permanecem sensíveis até cerca de 900 km a montante da foz do rio (Kosuth et al., 2009). Um dos desafios no *continuum* hidráulico do trecho baixo do rio Amazonas é a compreensão dos papéis relativos da força a montante e da influência oceânica na formação dos padrões espaciais e temporais de variabilidade do nível da água, velocidade de fluxo e extensão de inundação ao longo do curso do estuário. Iniciativas promissoras têm sido feitas para modelar este complexo estuário, principalmente contando com modelos de circulação oceânica costeira, seja em configurações bidimensionais (Gabioux et al., 2005; Gallo e Vinzon, 2005), ou, mais recentemente, por meio de modelagem tridimensional completa (Molinas et al., 2020). Esses estudos, em particular, lançaram luz sobre o comportamento distinto das ondas marítimas durante sua propagação a montante no estuário Amazônico. No entanto, até o momento, falta uma estrutura de modelagem hidráulica abrangente e de alta resolução, que abrace a complexa geometria de todo o *continuum* hidráulico do baixo rio Amazonas, e contabilize toda a gama de interações entre os fatores forçantes do oceano e do rio. Isso pode ser explicado, pelo menos parcialmente, pelo fato de que o monitoramento da variabilidade do nível da água é fundamental no sucesso de uma modelagem hidráulica do trecho baixo do rio Amazonas para fins de calibração/validação; no entanto, a altimetria por satélites tem sido pouco utilizada no estuário Amazônico. Finalmente, os novos dados de observação da Terra por satélite, como os níveis da água derivados do SWOT (Biancamaria et al., 2016), largura dos canais de água (Allen e Pavelsky, 2018; Yamazaki et al., 2014), topografia das planícies de inundação (Fassoni-Andrade et al., 2020b), e estimativas de umidade do solo (SMOS, SMAP), bem como novos conjuntos de dados de precipitação, por exemplo aquelas oriundas do uso de dados de umidade do solo como o SM2RAIN Brocca et al., 2013, 2014), missões de gravimetria (GRACE *Follow-On*), e técnicas para recuperar armazenamentos de águas subterrâneas (por exemplo, Frappart et al., 2019), irão abrir grandes oportunidades para a próxima década de desenvolvimento de modelagem hidrológica e hidráulica na bacia Amazônica.

Um dos principais objetivos da comunidade de modelagem na Amazônia deve ser avançar em direção a modelos de hiper-resolução, capazes de fornecer estimativas localmente relevantes em todos os lugares (Bierkens et al., 2015; Fleischmann et al., 2019; Wood et al., 2011), bem como representando melhor todos os processos dentro do ciclo da água, incluindo a dinâmica das águas subterrâneas que é tipicamente mal representada na maioria dos modelos hidrológicos, normalmente focados nas águas superficiais (Miguez-Macho e Fan, 2012; Sutanudjaja et al., 2018). O avanço em direção a modelos de hiper-resolução foi promovida em escala global devido ao desenvolvimento de novos métodos numéricos, conjuntos de equações e engenharia de software, bem como, ao aumento da capacidade computacional (Bates et al., 2018). Tais sistemas de modelagem poderiam, então, ser acoplados a modelos de outros processos, como feito recentemente por pesquisadores com o objetivo de compreender os impactos das inundações na fotossíntese e na biosfera em geral (Castro et al., 2018), as interações entre águas superficiais e atmosfera (Santos et al., 2019), as exportações de sedimentos e armazenamento em planícies (Fagundes et al., 2021; Rudorff et al., 2018), o armazenamento de carbono e as emissões através de áreas úmidas e terra firme (Hastie et al., 2019; Lauerwald et al., 2020), e a dinâmica dos ciclos biogeoquímicos em escala da bacia ou sobre áreas úmidas (Guilhen et al., 2020). Todos esses esforços exigirão dados adicionais de SR e avançarão a nossa capacidade de projetar os efeitos das mudanças ambientais em curso na bacia Amazônica.

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