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The value of hydrologic information for watershed management programs: The case of Camboriú, Brazil

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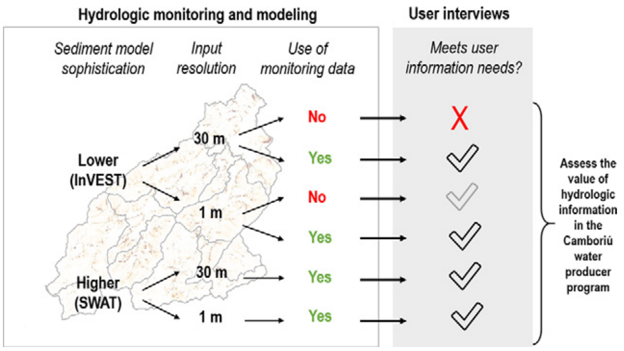
HIGHLIGHTS

- We explore how hydrologic information is used in watershed management programs.
- We analyze interviews, and hydrologic modeling and monitoring (HMM) data.
- In practice HMM data was not used to support program design and implementation.
- Model sophistication and data availability improved the credibility of information.
- Interdisciplinary approaches should inform the design of HMM activities.

GRAPHICAL ABSTRACT



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ABSTRACT

Investments in watershed services programs hold the promise to protect and restore ecosystems and water resources. The design and implementation of such programs is often accompanied by hydrologic modeling and monitoring, although the role of hydrologic information in meeting the needs of program managers remains unclear. In the Camboriú watershed, Brazil, we explored the value of hydrologic modeling and monitoring with respect to two dimensions: scientific credibility and use of generated knowledge in the design, implementation, and evaluation of the watershed management program. We used a combination of semi-structured interviews, focus groups, and hydrologic modeling under various levels of data availability to examine when improved models and data availability might build credibility and provide more useful information for decision makers. We found that hydrologic information was not actually used for the detailed design, but rather contributed to broad-scale support of the program by increasing scientific credibility. Model sophistication and data availability improved the credibility of hydrologic information but did not affect actual decisions related to program design. Hydrologic monitoring data were critical for model calibration, and high-resolution land use and land cover data,

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obtained via remote sensing, affected some model outputs which were not used to design the program. Our study suggests that identifying how hydrologic data will inform decision making should guide the level of effort used in hydrologic modeling and monitoring.

1. Introduction

Around the world, investments in watershed services (IWS) programs represent a key opportunity to protect and restore water resources and natural ecosystems (Salzman et al., 2018; Vogl et al., 2017). These programs, which include Payments for Ecosystem Services, Water Funds, and local variations such as Water Producer Projects in Brazil (Bremer et al., 2016a; Richards et al., 2015), seek to create mutually-beneficial agreements between upstream and downstream actors in a watershed. They are often designed to mobilize resources contributed by downstream actors to compensate upstream actors for managing landscapes in a way that is believed to improve or maintain water resources and other environmental benefits.

The process of initiating, designing, and implementing an IWS program requires participation from a range of upstream and downstream actors. Downstream actors must decide if a program is worthwhile and then provide political and financial support, while upstream actors who own or manage land must agree to implement on-the ground projects. Motivations for participation have been the object of extensive debate within the world of IWS (Bremer et al., 2014; Figueroa et al., 2016; Santos de Lima et al., 2019). On the one hand, neoclassical economics theory supports an economic rationale for participation (Wunder, 2005): it suggests that downstream investors require a positive return on investment or at least assurance of a cost-effective investment (Kroeger et al., 2019; Murdoch et al., 2007), while upstream actors are concerned about the opportunity cost of participation (Pattanayak et al., 2010; Salzman et al., 2018). This view implies that actors are driven by the hydrologic performance of a program (i.e. whether it improves water resources or not), meaning that improving the science underlying these programs will increase engagement and ensure greater success (Naeem et al., 2015). On the other hand, there is accumulating evidence that financial returns are often not the main motivations behind participation of both upstream and downstream actors (Bremer et al., 2018; Santos de Lima et al., 2019). Often, programs represent a social contract that has potential to improve water resources, promote environmental protection, and provide sources of livelihoods which both upstream and downstream actors are concerned with (Chan et al., 2017; Shapiro-Garza, 2013a, 2013b).

Notwithstanding, the assumption that improved accuracy in hydrologic modeling and monitoring will increase project success remains widespread (Taffarello et al., 2017). The research agenda in the field of water resources management has evolved accordingly, with new modeling approaches and monitoring protocols being developed to answer questions such as: what will be the change in water quantity or water quality following IWS interventions? Where should interventions be prioritized to achieve the highest impact? (Guswa et al., 2014; Hamel et al., 2018). In practice, hydrologic information answering these questions may be used for at least two purposes: strategically, to establish the scientific credibility of the program, and instrumentally, to design and evaluate the potential performance of a program (McKenzie et al., 2014). Strategic information is used to inspire or convince other parties to engage. Instrumental information is used by program managers to design and implement the program. From both perspectives, investing time and resources into hydrologic modeling and monitoring is potentially useful to consolidate the scientific basis of an IWS program.

However, investments to improve hydrologic information are expensive. IWS are usually constrained by limited resources (e.g. ability to run sophisticated models), data availability (e.g. pre-intervention baseline data), or logistics (e.g. access to monitoring sites) (Ponette-González et al., 2015; Santos de Lima et al., 2019). These constraints call for an efficient use of resources, in particular resources dedicated to watershed data collection and modeling at different stages of the project. From that standpoint, understanding how models and data are used and affect decision-making can help determine the adequate level of investment in scientific activities. Policy science suggests that to be effectively used in program design and implementation, information should be credible, salient, and legitimate (Cash et al., 2003). Analyzing this uptake requires defining what these attributes mean for a given project (Heink et al., 2015), which means engaging with the actors (potentially) involved in the program.

The motivation for this paper is to explore the role of hydrologic modeling and monitoring in the context of an IWS program, to guide appropriate investments in such scientific activities. We use the case study of the Water Producer Project (WPP) in Camboriú, Brazil, to address two questions: what is the value of hydrologic information to different decision-makers connected to the WPP? And how would improved models and monitoring data affect predictions and the decisions they inform?

Our methods combine project evaluation through semi-structured interviews and focus groups with hydrologic modeling given different levels of requirements for skills and data availability. The modeling analyses are conducted with SWAT (Soil and Water Assessment Tool) and InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs), two commonly used models in IWS design. Both models present multiple advantages for IWS programs: they are open source, have the ability to represent land-use change effects on several hydrologic variables (annual streamflow, sediment and nutrient concentrations), and have an active user community that continuously improves the models and their interpretation (Francesconi et al., 2016; Posner et al., 2016). However, the models differ in their temporal resolution (sub-daily for SWAT vs. annual for InVEST) and the data and skill requirements to run them (Vigerstol and Aukema, 2011). As such, they represent two different levels of model sophistication that can be drawn upon to illustrate the implications on resources for modeling and monitoring activities. By combining hydrologic modeling analyses with stakeholder interviews and focus groups aimed at understanding the actual use of information in the Camboriú WPP, our paper illustrates the value of interdisciplinary approaches to support IWS programs.

2. Materials and methods

2.1. The Camboriú water producer project

2.1.1. Description

The Camboriú watershed, in the Santa Catarina State of Brazil, is home to approximately 210,000 people, the majority of whom live in the cities of Camboriú and Balneario Camboriú. The watershed has an area of 200 km^2, dominated by forest (67%) but with significant land areas covered by pasture (16%), tree plantations (8%), and rice paddies (7%). The climate is humid subtropical (Köppen classification: Cfa), with rains year round, hot summers, and a mean annual temperature of 21 °C (Kroeger et al., 2019).

Over the past decades, water supply in this watershed has been unreliable, in large part due to increased demand by domestic and international tourists, who increase the population nearly 4-fold to almost 800,000 during the tourist season (December–March). High levels of sediment in the source water are an additional problem for EMASA, the water company of the municipality of

Balnearío-Camboriú. Sediment leads to increased water losses and treatment costs. As part of a legal mandate to invest in watershed protection, and to address the issue of sediment pollution, EMASA decided to develop and fund the Camboriú WPP, in partnership with The Nature Conservancy, the City of Camboriú, the Watershed Committee of Rio Camboriú, the Regulatory Agency for Public Services of Santa Catarina (ARESC), the Santa Catarina State Center for Environmental Information and Hydrometerology (CIRAM-EPAGRI), and the National Water Agency (ANA) (Klemz et al., 2016; Kroeger et al., 2019). The main objective of the WPP is to reduce sediment loads by protecting and restoring forest and managing dirt roads (Klemz et al., 2016). Following Brazil's Forest Code, restoration activities focus on degraded riparian areas, areas surrounding natural springs, and degraded upland forest on steep slopes –although as detailed in Section 4.1, the program currently works in the entire area without geographic preferences. Conservation activities consist of fencing to exclude cattle from riparian areas and protection of priority forests. Up to 2019, 66 ha had been restored and 1086 ha had been protected. Such activities are realized through direct payment to landholders enrolled in the program.

2.1.2. Scientific research in the Camboriú WPP

The Camboriú watershed was selected as it has received international recognition for its potential to demonstrate effectiveness through hydrologic modeling and monitoring, making it an interesting case study both for hydrologic modeling and its rich history of stakeholder involvement (Klemz et al., 2016; Kroeger et al., 2019). As for many tropical watersheds, the effect of restoration and conservation interventions in the Camboriú watershed are difficult to predict due to several challenges: fundamental knowledge gaps (e.g. local or watershed-scale processes or lack of monitoring data) (Ponette-González et al., 2013); modeling challenges (e.g. availability of relevant data or hydrologic models, inadequate treatment of uncertainty) (Hamel et al., 2018); and implementation challenges (e.g. accounting for local socio-political constraints, which may not be transferrable across regions). To address these challenges, several studies have been conducted in Camboriú to improve understanding of the watershed and the cost-effectiveness of the WPP.

Blainski et al. (2017) developed a SWAT model of the watershed to simulate the impact of land-use change on flows and sediment concentration. They showed that historic land-use change, towards more agriculture (rice fields) and urbanization, led to higher peak flows, lower baseflow, and higher sediment loads, confirming the exacerbation of water supply challenges observed by EMASA. Kroeger et al. (2019) developed a SWAT model of the watershed to conduct a return on investment analysis for the Camboriú WPP by estimating sediment concentration under projected interventions and under a counterfactual scenario where current trends in land-use change are projected into the future. They found that in the absence of third-party investment, the return on investment was negative if only sediment benefits were accounted for, but conservative assumptions about co-benefits were sufficient to increase the return on investment above 1. Fisher et al. (2018) investigated the effect of improved remote sensing data on sediment yield predictions. They found that higher resolution satellite imagery (1 m) usually predicted sediment loads better than coarse resolution imagery (30 m). Through a return on investment analysis, they showed that discrepancies arising from data resolution could have impacted decisions to invest, but that the actual decision maker would have invested regardless of which approach was used. Most of these studies make use of monitoring data that has been collected since 2014 (Bremer et al., 2016b), also used in our study. Our present contribution is to study the potential usefulness of a model with lower data and skill requirements, and to assess the value of information generated by models through analyzing actual user needs.

2.2. Methods overview

Our goal is to examine the role of hydrologic modeling and monitoring in the context of the Camboriú WPP by addressing two questions: what is the value of hydrologic information to different decision-makers connected to the WPP? And how would improved models and monitoring data affect predictions and the decisions they inform? We first conducted key informant interviews as well as focus groups with a range of WPP actors to understand their use and desired use of hydrologic information in program design and implementation. We then examined results from two models of sediment yield with different levels of sophistication, InVEST and SWAT, to explore their potential to address WPP-relevant questions. We distinguished two main goals for hydrologic modeling: i) spatially targeting interventions, which can increase cost-efficiency, and ii) assessing the impact of interventions on sediment yield, to estimate the effectiveness of the program relative to its hydrologic objectives. Finally, we examined the value of local monitoring climate and sediment data for calibration, as well as higher resolution LULC input data.

2.3. Stakeholder perspectives

To understand the role of hydrologic information in motivating WPP participation and in influencing program design and implementation, we conducted semi-structured interviews with the majority of representatives of the Project Management Unit (the primary decision making body) member organizations (7 out of a total of 8 organizations) as well as 3 of 13 participating landholders. This included Municipal representatives from Camboriú (1) and Balneario Camboriú (2), The Nature Conservancy, EMASA (the municipal water company), FUCAM (Environmental Foundation of Camboriú), The National Water Agency (ANA), and CIRAM-EPAGRI (the State Environmental Monitoring Agency). Interview questions focused on stakeholder roles and objectives, motivations for and process of joining the program, perceived metrics of success, and perceptions of current and potential use of hydrologic information (Bremer et al., in review). We followed similar themes as explored in previous studies of stakeholder motivations and goals and program design in Investments in Watershed Services Programs (Bennett and Carroll, 2014; Bremer et al., 2014; Farley et al., 2011).

We also carried out three focus groups with participating landholders, which similarly focused on motivations, the use of hydrologic information, as well as their ideas for improving the structure and design of the project (Wilburn et al., 2017). Interviews and focus groups were carried out in October–November 2016 and in June–July 2017. We complemented primary data collection with document review of the Camboriú WPP and the WPP program in general to understand the generation and use of hydrologic information and perspectives on the legal context and motivations for the project (ANA, 2012; Klemz et al., 2016; Kroeger et al., 2019).

Interviews were recorded and transcribed whereas detailed field notes were taken for the focus groups. We then compiled key metrics of success, motivations and/or obstacles for participation, and perceived information needs for each stakeholder group. We complemented and compared this to accounts of stakeholder motivations in existing documents.

2.4. Hydrologic modeling

2.4.1. SWAT model

SWAT is a commonly used rainfall-runoff model that can simulate flow and sediment yields at sub-daily to annual time scales (Francesconi et al., 2016). Due to its large number of parameters, model use requires a robust parameterization and calibration procedure, and advanced modeling skills. Here, we used the SWAT model parameterization produced by Fisher et al. (2018) and extracted outputs for the year 2016. The model was set up with land-use/land-cover maps from 2012, and a rainfall time series from the Louro station (Fig. 1) (1-m and 30-m resolutions, see Section 2.5 and Appendix B for details). It was calibrated based on hourly time series of turbidity (converted to sediment concentration) from two stations: Canoas and EMASA (Fig. 1). Additional details including data sources are provided in the Appendix A.

2.4.2. InVEST model

The InVEST (v3.6) sediment delivery ratio model is commonly used in ecosystem services assessments (Hamel et al., 2015). Contrary to the SWAT model, InVEST requires a low number of parameters and relatively low modeling skills. The model uses the universal soil loss equation (similar to SWAT, which uses a modified version of the equation) and routing algorithm that estimates the proportion of eroded sediment that is deposited on the landscape before reaching the stream. Specifically, the model calculates eroded sediment as:

$$\mathrm{USLE} = \mathrm{R} * \mathrm{K} * \mathrm{LS} * \mathrm{C} * \mathrm{P}$$

And sediment yield as:

$$\mathrm{SY} = \mathrm{USLE} * \mathrm{SDR}$$

where R is rainfall erosivity (MJ mm $(\text{ha hr})^{-1}$), K is soil erodibility (t ha hr $(\text{MJ ha mm})^{-1}$), LS is a slope length-gradient factor (unitless), C is a crop-management factor (unitless), P is a support practice factor (unitless), and SDR is the sediment delivery ratio (routing parameter calculated based on the digital elevation model and the C factor) (Sharps et al., 2017b). The model outputs annual sediment export (for one or several years, according to the duration of the rainfall erosivity factor), and calibration consists in matching this value to observations. The model was tested in several locations around the world and its performance was satisfactory, especially after calibration (Hamel et al., 2017).

The model was parameterized and calibrated for the Camboriú watershed with input data matching SWAT's input data to the extent possible (see Appendix A). For some layers, we made minor changes to allow successful execution of the InVEST model: specifically, we applied a filling algorithm (Wang and Liu, 2006, implemented in Qgis) to the digital elevation model layer to allow consistent flow routing in InVEST. For climate data, we used two different sources: a national dataset of average precipitation over 34 years, from 1980 to 2013 (Xavier et al., 2016) and the 2016 data from the Louro climatic station (see Appendix A). Sediment yield for the year 2015 predicted by the SWAT model was used as calibration data for InVEST since observed sediment data time series had gaps and could not be used directly to calculate annual sediment yield. The annual estimate of sediment yield was 15,823 t (1.15 t ha^{-1} yr^{-1}) and 5280 t (or 1.09 t ha^{-1} yr^{-1}) for EMASA and Canoas stations, respectively (for the year 2015, Fisher et al., 2018).

2.4.3. Future land use scenarios

We compared the two models based on two modeling goals. First, we examined the priority sites for restoration predicted by each model. These sites were determined by selecting the pixels with the

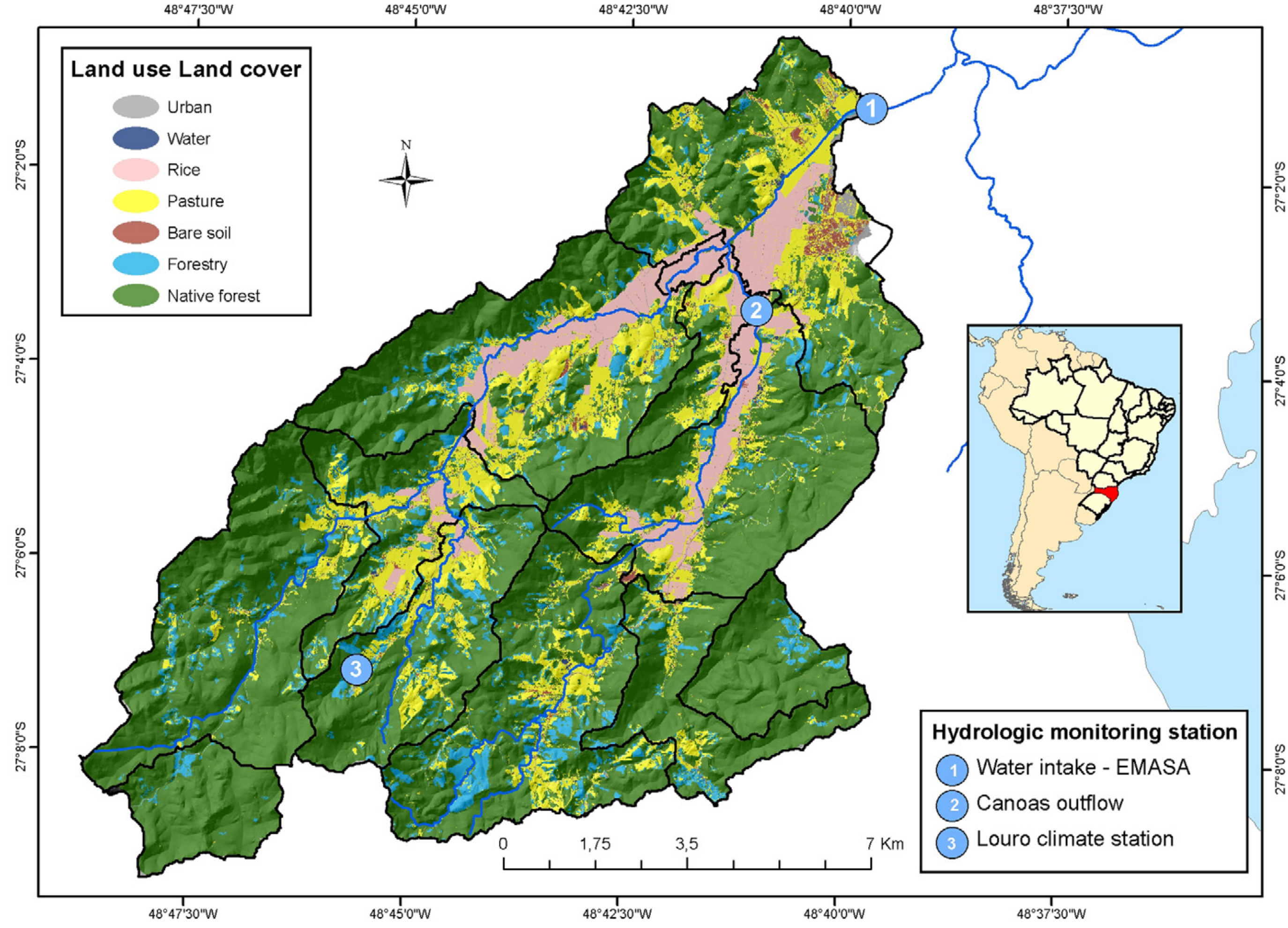

Fig. 1. Location of the Camboriú watershed in Brazil, land use categories, and location of hydrologic monitoring stations.

highest sediment export rates, as predicted by each model, up to an area of 326 ha. This value was an initial target based on the implementation capacity of the program (Kroeger et al., 2019). Second, we compared the impact of planned interventions on sediment yield in the watershed in 2025. The 2025 scenario was developed based on a counterfactual land-use/land-cover scenario obtained by projecting current trends in land-use change into the future, and comparing results with and without interventions (see details in Kroeger et al., 2019). In addition to these projected changes (resulting from external drivers), two types of interventions were represented: 326 ha were restored, in areas where sediment export (as predicted by the 1-m SWAT model) was the highest, and 313 ha were conserved, in areas where forests were likely to be converted to other land uses (Kroeger et al., 2019). The comparison metric was the annual sediment yield, since InVEST only provide annual values.

2.5. Improved land-use/land-cover, climate and sediment data

2.5.1. High-resolution land-use and land-cover

To assess the value of using higher land-use and land-cover (LULC) resolution, each model was run first with the default resolution of LULC (30 m), and then with a higher resolution layer, acquired by The Nature Conservancy (Fisher et al., 2018). SWAT was run with 1 m resolution data, while the raster was resampled to 10 m resolution for InVEST, to reduce computational requirements. By comparing the results for the two outputs of interest (intervention sites and change in sediment yield), we assess the value of high-resolution data for each model.

2.5.2. Climate and sediment monitoring data

To assess the value of monitoring data, we analyzed data collected from the hydrologic monitoring network implemented with the WPP that includes hourly and daily time series of precipitation, stream depth, and turbidity for different periods between 2014 and 2017. First, to determine the uncertainty introduced by the climatic input, we compared the estimates of annual rainfall erosivity calculated using the regional relationship (see Section 2.4.2) with estimates derived from hourly precipitation data from the Louro station (Fig. 1) for 2016. Next, to assess the value of the sediment monitoring data, we compared the InVEST model with and without calibration data obtained from the monitoring network. In addition, we compared modeled annual sediment yield ($t\ ha^{-1}\ yr^{-1}$) with yields calculated using hourly and daily measurements of water turbidity (NTU) and stream depth (cm) for the years 2014, 2015, and 2016. Additional details on the pre-processing of the climate and sediment data are provided in Appendix B. We examined overall relationships between daily precipitation and sediment yield data as well as by year and season (dry: April–September, and wet: October–March).

3. Results

3.1. Stakeholder information needs

3.1.1. Upstream engagement

Our focus groups and landholder interviews suggest that formal hydrologic information does not play an important role in motivating participation in the WPP by upstream landholders. At the time of our research, there were challenges in recruiting landowners due to a long-history of distrust of institutions and resistance to the idea of locking up land. The socio-political situation makes relationship building between the program and long-term residents even more complex. The municipality of Balneário-Camboriú is wealthier than Camboriú (where the source watershed is) and while EMASA supplies water to both Camboriú and Balneário-Camboriú, historically water shortages during the high tourist season in Balneário-Camboriú have led to water being cut off for the less wealthy residents of Camboriú, causing substantial distrust. There is also a long history of distrust between landholders and municipal environmental regulators. Given these challenges to participation, the program has focused on raising awareness on the broader benefits of environmental conservation and build trust among landholders who were willing to join the program. Instead of highlighting the sediment reduction benefits for EMASA, the program highlighted other benefits such as biodiversity protection. In fact, most of the landowners who first enrolled in the project did so because they wanted to conserve or restore particular areas. In time, it is hoped that other landowners will also enroll after seeing well implemented and fair cooperative agreements established with their neighbors. Moreover, while historically the Forest Code has not been well enforced, this situation is changing, leading to perceived benefits in terms of financial capital needed to meet restoration requirements.

3.1.2. Program managers

The prioritization exercise conducted by the Camboriú WPP managers aimed to identify areas that generate the most sediment and should thus be first enrolled in the project (Kroeger et al., 2019). However, given existing challenges with distrust, the program currently does not use this information and has enrolled any landowner in the basin who is willing. They have also allowed landholders to determine what parts of their land to enroll in an effort to make the program more attractive. As noted above, the first landholders were generally conservation minded, and joined the program to achieve biodiversity protection goals and for the incentive. The intention of the program in working with them was to increase visibility in the watershed and build social capital so that other landholders would eventually also feel comfortable enough to enroll. Therefore, hydrologic modeling did not play a significant role in the engagement strategy developed by program managers.

3.1.3. Downstream stakeholders

For downstream stakeholders, we did not find strong reliance on modeling as a motivation for program initiation. The legal context may explain this finding. The water utility, EMASA, is required to invest 1% of its budget in the watershed where water is supplied (Bremer et al., in review). This means that funding was potentially available, but a case had to be made for investing in conservation and restoration activities. A local champion working with EMASA learned of the idea of Water Producer Projects after visiting another program in Brazil, and started promoting the idea for Camboriú, convincing The Nature Conservancy to participate and then help design and launch the program. Therefore, persistence of a local champion, coupled with a legal framework requiring EMASA to take some action, were critical to success.

The fact that the program successfully got off the ground without any modeling exercises may also maybe be explained by two factors. First, quantifying the extent of sediment reduction was not necessary, as stakeholders recognized evidence from other sources that watershed management could reduce sediment loads and water treatment costs. Second, the alternatives to protect water supplies other than investing in the WPP were unappealing. The two primary alternatives under consideration were inaction (highly unappealing given the increasing risk of water shortages) and building a pipeline to a neighboring watershed to source water from (which was expensive and ran the risk of the other watershed having similar sediment problems as land use change progressed). The nature of the alternatives eased the decision to invest in the WPP without the need for sophisticated model of the watershed.

Over time, however, stakeholder desire for scientific information has increased. The Nature Conservancy sees Camboriú as a replicable model, one based on working with water regulators to include the costs of watershed conservation in water tariffs as the State water regulator (ARESC) had done for EMASA. Monitoring and modeling remain an important part of the work as the NGO positions itself as a conservation organization driven by science and as it seeks to enhance the credibility of this approach across Brazil. Other stakeholders with a scope beyond Camboriú (e.g. the environmental monitoring center, CIRAM-EPAGRI, or the national water agency) also noted the importance of Camboriú as a demonstration site, which can be replicated in other regions. From the perspective of CIRAM-EPAGRI, Camboriú is an opportunity to demonstrate the benefits of ecosystem conservation and restoration through a concerted monitoring program (Klemz et al., 2016). Municipal members of the Project Management Unit emphasized the importance of monitoring and evaluation beyond sediment, including biodiversity monitoring, social monitoring, and evaluation of sewage impacts on aquatic and marine resources.

In summary, these results indicate that in the Camboriú WPP, hydrologic information was not used instrumentally to initiate or design the program, but rather, in a second phase, to promote and evaluate the program in other places (strategic use of information). The characteristics of specific information needs from different stakeholders are further explored in a separate paper (Bremer et al., in review).

3.2. Impact of model calibration and sophistication on hydrologic information

3.2.1. Model calibration

Prior to calibration, the InVEST model with a resolution of 30 m estimated sediment yield at 2 t ha^{-1} yr^{-1}, overestimating annual sediment yield by 76% as compared with SWAT. This means that the model failed to meet a basic criterion of credibility, which we define based on the findings of Section 3.1 as model credibility for strategic use of information (Fig. 2): here, it meant that the model should adequately represent sediment yield and changes in sediment yield under land use change. Given the simple structure of the InVEST model, calibration process consisted in varying the calibration parameter (k) to match the sediment yield at the EMASA station (estimated from SWAT, see Section 2.4). We decreased the value of k by increments of 0.1 and found the best match for $k = 1.6$, which resulted in an estimated sediment yield of 1.04 t ha^{-1} yr^{-1}, i.e. a relative difference of −9.6%. Importantly, we verified that the same value of the calibration parameter also was a good fit for the second data point (Canoas station). The relative difference was similar (−11.3%) for that station, suggesting that the calibrated model was able to represent (small) differences in land use. This means that the calibrated model is credible (Fig. 2), since its structure has been validated elsewhere (Hamel et al., 2017) and we were able to match the local annual sediment yield at two different stations.

The SWAT model with a resolution of 30 m was calibrated using daily streamflow and sediment data from two hydrologic stations (EMASA and Canoas, see Fig. 1) for part of 2014 (see details in Fisher et al., 2018). Model performance was satisfactory for Canoas and poor for EMASA station: for the validation period in 2015, Nash-Sutcliffe Efficiency values for streamflow were equal to 0.51 and 0.16 (for Canoas and EMASA stations, respectively), corresponding to a bias of 18.1% and − 4% (respectively).

3.2.2. Intervention siting

The targeting of intervention sites at 30 m resolution differed between the two models (Fig. 3), with only 17% of the pixels being selected by both models. When data were aggregated at a coarser resolution to provide general guidance on which areas should be prioritized for interventions, differences between the two models decreased. Specifically, when aggregated at a resolution of 3 km, the spatial correlation between priority areas was high (Spearman rank = 0.86). This was also true at the subwatershed level (with the 12 subwatersheds delineated in Fig. 1): when targeted pixels were aggregated at the subwatershed level, the ranking of subwatershed was similar between the two models (Spearman rank = 0.73).

The siting of interventions predicted by InVEST did not vary before or after calibration, due to the model structure: varying the calibration parameter value affects all pixels proportionally, which means that their respective ranking is not affected by the process, so intervention targets remain unchanged. The discrepancy in intervention siting between the two models was not considered when assessing the adequacy of the model (meeting user information needs, i.e. model credibility, in Fig. 2) since this type of information was ultimately not needed by stakeholders (Section 3.1).

3.2.3. Impact of future land-use change and interventions

Based on the SWAT model, the 2025 scenario reduced annual sediment yield by 28%, whereas the InVEST model estimated this reduction at around 42%. This represents a difference of about 1900 t yr^{-1}, which would affect the return on investment. The uncalibrated InVEST model estimated a 36% reduction in sediment export for the 2025 scenario, i.e. a value closer to the SWAT model.

The total reduction was driven by major reductions in some subwatersheds, while others showed only small differences in sediment yields (Fig. 4). This spatial variation is due to uneven distribution of future land-use changes across the watershed (Fig. 3 represents the spatial distribution of restoration interventions, which add to other hypothetical land-use changes described in Section 2.4.3).

3.3. Impact of high-resolution LULC data

For the SWAT model, the higher resolution data (1 m) generally yielded a higher performance during calibration and validation: for

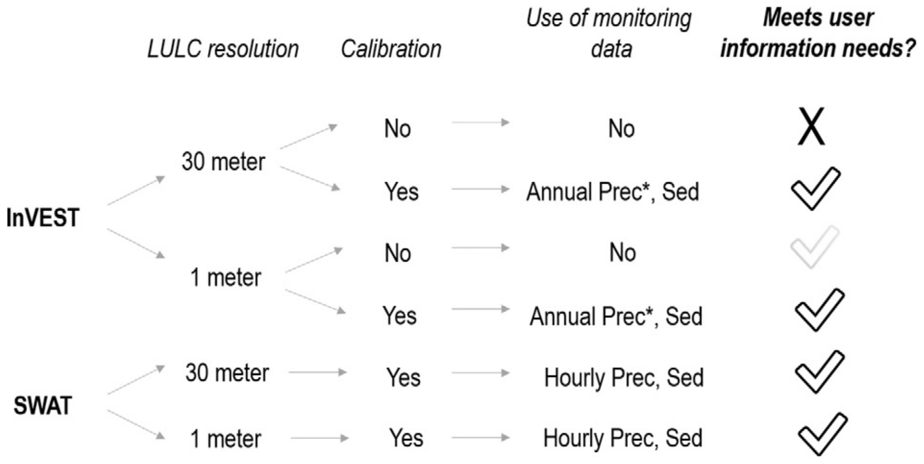

Fig. 2. Comparison of the six models used in this study with their respective LULC resolution, and set-up requirements (calibration, potential use of monitoring data, and whether or not they meet user information requirement). Information needs are defined as model credibility for strategic use of information (since information was not used instrumentally, see Section 4.1). * indicates that monitoring data could be used to improve credibility. The grey check for the 1 m InVEST model indicates that the model met information needs but this was likely due to chance (see Section 4.3).

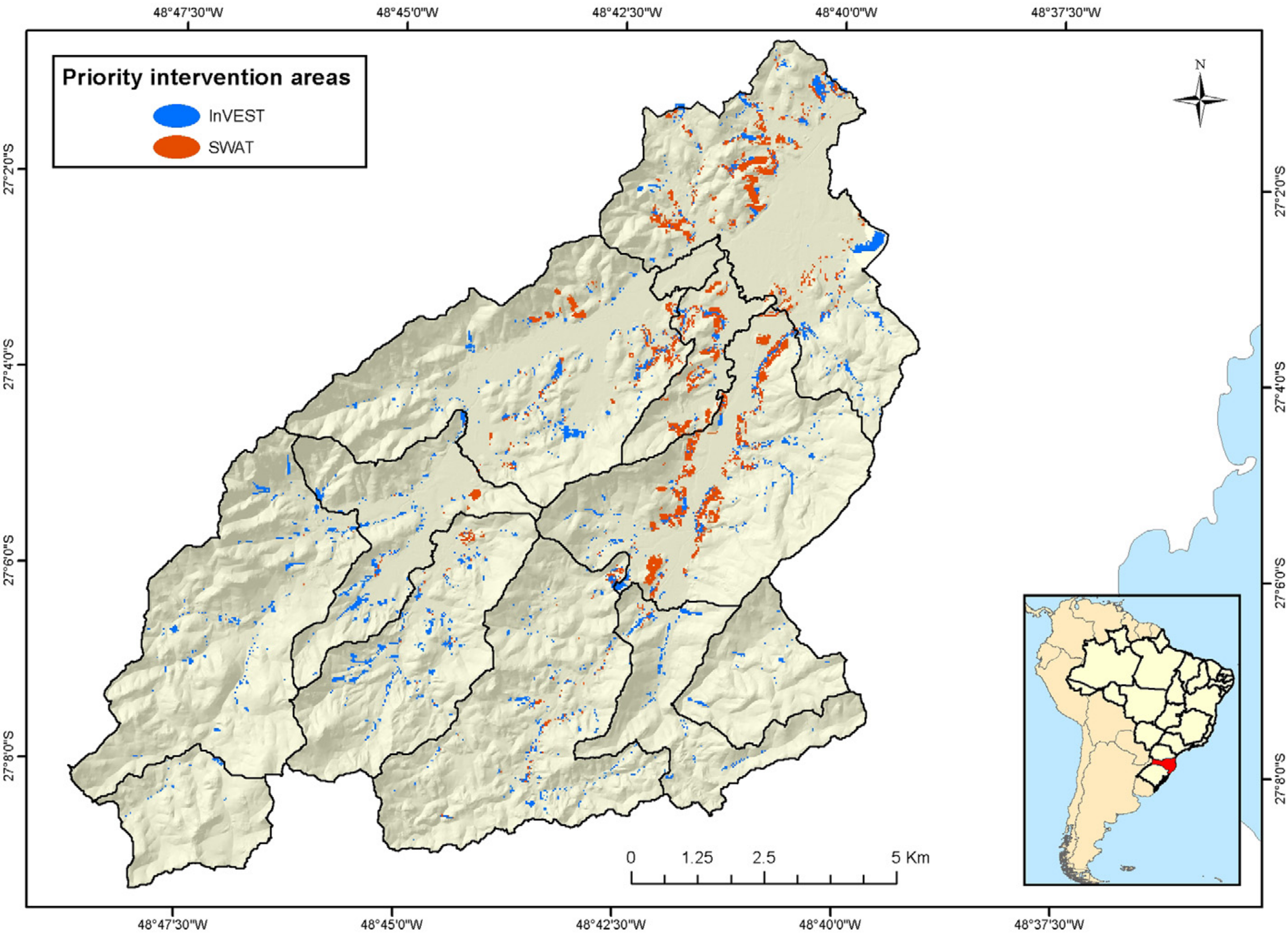

Fig. 3. Identification of priority intervention areas for restoration according to highest current sediment export values estimated from the InVEST and SWAT models with 30-m resolution land-use/land-cover data.

the EMASA (water intake) station, the validation NSE went from 0.16 to 0.48 from 30 m to 1 m (Fisher et al., 2018). The InVEST model results also improved with input resolution. The uncalibrated model ($k = 2$) yielded a value of sediment export of 1.18 t ha^{-1} yr^{-1}, a difference of <3% from the reference value (prediction from the 1 m SWAT analysis, 1.15 t ha^{-1} yr^{-1}). This good match means that the model did not

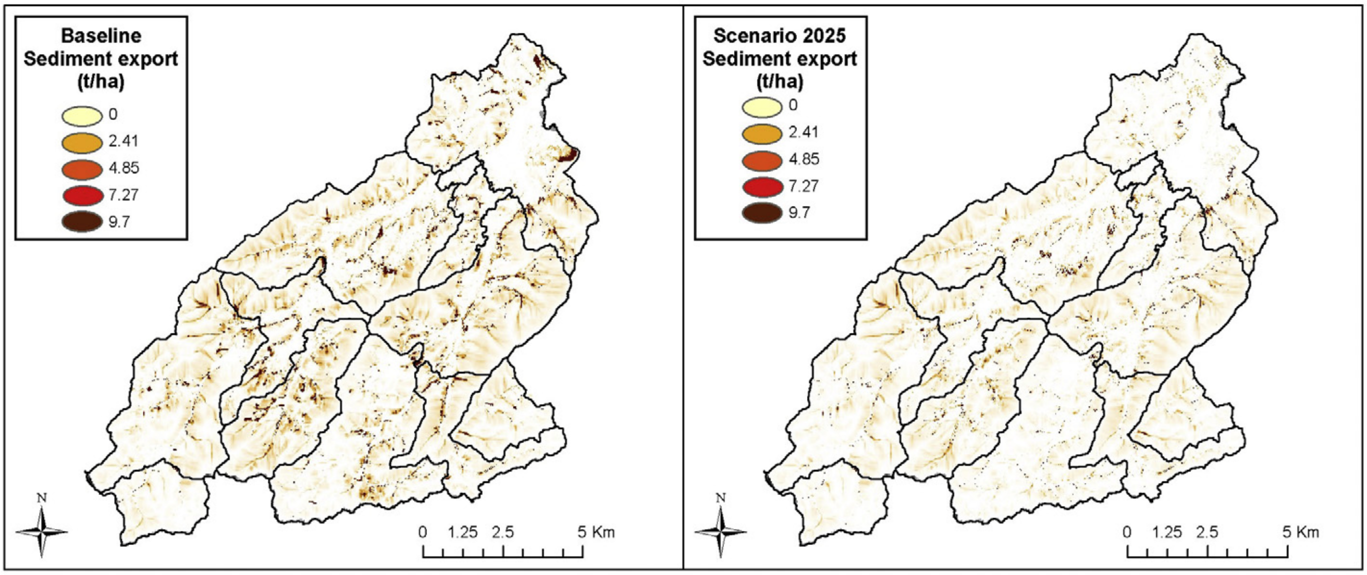

Fig. 4. Sediment export estimated by the InVEST model for the baseline and 2025 scenario with 30-m resolution land-use/land-cover data.

require further calibration. We also tested whether the higher performance was due to the introduction of new information (mainly new roads represented in the landscape) or simply a model artifact related to the change in resolution, by resampling the 30 m LULC cover to 10 m. This yielded a value of 2.09 t ha^{-1} yr^{-1}, very close to the 30 m resolution results (2.02 t ha^{-1} yr^{-1}), suggesting that the introduction of new information, rather than the resolution, was driving the results. Therefore, it seems likely that the good match between the uncalibrated value and the reference value was due to improved LULC information; however, given that the model tests globabally suggest that calibration is always recommended (Hamel et al., 2015), the good performance in the Camboriú watershed does not indicate that the model can generally be used without calibration (Fig. 2).

The siting of interventions was also affected by the LULC resolution: only 29% of the target restoration pixels overlapped between the InVEST model outputs at 10 m and 30 m resolution. When comparing with the SWAT results, 22% of the target restoration pixels were selected by both the SWAT and InVEST models (after disaggregating the SWAT target restoration areas from 30 m to 10 m), i.e. 5% more than with the 30 m resolution.

3.4. Insights from monitoring data

Annual erosivity calculated from the Louro time series in 2016 was 5178 MJ mm ha^{-1} h^{-1} yr^{-1}, within the range of values reported by Panagos et al. (2016) and Oliveira et al. (2012) for this climate zone and area and region of Brazil, respectively. Annual erosivity calculated using the national dataset (Xavier et al., 2016), which was used in InVEST, was nearly two times higher (9565 MJ mm ha^{-1} h^{-1} yr^{-1}). This difference could explain the large overestimation of the uncalibrated model.

Sediment yields calculated using the Canoas monitoring data ranged nearly 10-fold across the three years: 0.58, 1.1, and 5.6 t ha^{-1} yr^{-1} in 2014, 2015, and 2016, respectively. The mean annual sediment yield was 2.4 t ha^{-1} yr^{-1}, much higher than the mean for 2014 and 2015 only (which was used for the model calibration). We found a weak but significant positive relationship between daily precipitation and sediment yield ($R^2 = 0.15$; $p < 0.0001$). The relationship between daily precipitation and sediment yield was stronger when the data were analyzed separately by year ($R^2 = 0.27$; $p < 0.0001$ for both 2015 and 2016). Not surprisingly, precipitation was more strongly related to sediment yield during the wetter ($R^2 = 0.20$; $p < 0.0002$) compared to the drier season ($R^2 = 0.10$; $p < 0.0284$).

4. Discussion

The objective of this study was to understand the value of hydrologic modeling and monitoring for both upstream and downstream actors in the context of designing and implementing a WPP. Evaluation of integrated environmental modeling projects remains rare due to insufficient time and resources, lack of incentives to highlight shortcomings of the project, or simply lack of awareness or recognition of the benefits of project evaluation (Hamilton et al. 2019). High quality hydrologic information is often assumed to be relevant to the creation and implementation of IWS programs, but there is little evidence that such information effectively changes decisions (Bremer et al., in review) or leads to more equitable and effective outcomes (Kolinjivadi et al., 2017). The contribution of this paper is to clarify the role that hydrologic modeling and monitoring information played in the Camboriú WPP. We acknowledge that our findings are specific to the study site and recommend further research to assess the validity of the results beyond the Camboriú WPP. In our research in two other Brazilian WPPs, we found similar evidence that hydrologic modeling played a relatively small role in program design and implementation (Bremer et al., in review). However, the hydrologic modeling findings are difficult to extrapolate and further model comparison exercises would help assess the advantages and drawbacks of sophisticated vs. easy-to-use tools (Sharps et al., 2017a; Vigerstol and Aukema, 2011).

4.1. The role of modeling and monitoring for WPP

Our findings indicate that hydrologic models (InVEST and SWAT) have not been used instrumentally, either to convince stakeholders to engage or to design or implement the Camboriu WPP (Kroeger et al., 2019). For example, to date the return on investment assessment has served as a proof of concept but was not needed to convince stakeholders or site investments. Rather, to initiate and implement the Camboriú WPP, trust building and personal relationships, alongside pre-existing environmental values have been most important. EMASA and The Nature Conservancy's early work and the co-development of the project through the creation of the Project Management Unit were critical in building trust and getting “downstream” buy-in. Our findings suggest that models have been used as a boundary object among downstream and broader scale actors including EMASA, The Nature Conservancy, and ANA to communicate a common understanding of the watershed and the potential impact of conservation interventions. In these circumstances, modeling approaches can remain simple and have low precision as long as this is clearly communicated to stakeholders and, above all, there is already a degree of mutual trust. Our findings corroborate earlier research on “boundary work” suggesting that in early stages of a project, information is mainly used for “enlightenment”, to advance understanding of the problem and explore possible solutions (Adem Esmail et al., 2017; Clark et al., 2016).

Hydrologic models (and monitoring) are, however, an important part of the broader strategy of demonstrating success to ensure long-term sustainability of the program and using it to replicate programs in other areas. This strategy is of greater interest to national or regional scale actors such as the water agency or NGOs like The Nature Conservancy, which illustrates that modeling needs differ among stakeholders. In addition, we note that demonstration of positive returns on investment may become more important through time. In an IWS program in Quito, Ecuador (FONAG), for example, the water company contributed data and supported a return on investment study in an effort to evaluate the impact their investments had had over 10 years. This evolution through time would be similar to the Fuhrberg watershed management program described by Adem Esmail et al. (2017), where earlier stages of the project only required the information to be credible to support discussions; only at later stages was the information used to inform specific decisions.

4.2. Scientific credibility and impact of improved models and data

To the extent that models do play a role, even though strategic or conceptual rather than instrumental, it is important to examine if a simple model with low data needs such as InVEST can provide the scientific credibility necessary to support a WPP. InVEST has much lower data and resource requirements compared to the commonly used SWAT model, and it does not represent the biophysical processes in detail. Our findings revealed four points, which we elaborate on in the next paragraphs: i) calibration data was critical to increase credibility but their remain high modeling uncertainties, ii) additional monitoring data is useful but difficult to interpret; iii) model sophistication did not affect the results deemed valuable by stakeholders; iv) improved LULC did change the results but did not necessarily influence the use of this information.

First, both models needed calibration to match observed sediment yields. This is evident for SWAT, whose complexity means it is scarcely used without calibration, but also for InVEST, whose performance is much improved with calibration data (Hamel et al., 2017). Importantly, we note that sediment data are highly uncertain, not only in Camboriú but across the world (de Vente et al., 2013). This is due to high interannual variability (as it is the case in our study, cf. Section 3.4), but also the complexity of sediment transport and associated monitoring challenges (de Vente and Poesen, 2005; de Vente et al., 2013). For our modeling purposes, the low quality of calibration data contributes to the uncertainty of absolute estimates of sediment export, as well as relative changes in future scenarios. Relatedly, there are no post-intervention observations, which makes it difficult to assess the confidence in future estimates. Our results also show that climate data are highly uncertain, since our two data sources different by almost 100%. Uncertainty in input data are a difficult problem to solve in hydrology, and requires long term, well-designed and well-resourced monitoring programs, which consider ecohydrologic processes relevant to the watershed management program (Taffarello et al., 2017). Our study highlights these uncertainties and represents an example of simple but important uncertainty assessment for ecosystem services models (Bryant et al., 2018).

Second, relatedly, we note that monitoring in Camboriú was designed as a model system to evaluate the impacts of IWS and contribute to an on-going monitoring program at the national scale (Klemz et al., 2016). However, even in this context, we found common challenges related to the design and maintenance of the monitoring program (Santos de Lima et al., 2019). Specific examples for Camboriú relate to the frequency, continuity, and spatial extent of data collection. Given the focus on sediment yield and the large body of literature on rainfall erosivity, precipitation data with a 30-min or higher resolution (as opposed to hourly) would be the optimal frequency for erosivity estimates. In addition, the discontinuity of data collection presented challenges for analyses. Because we lacked complete wet season data on sediment yield for 2015 and 2016, our estimates based on hydrologic monitoring are likely underestimates. Therefore, although SWAT has the advantage to represent event-scale sediment export, missing observations especially during the wet season decrease confidence in the calibrated values. Finally, the spatial coverage (with only two gauges with sediment yield data) limited a spatially-explicit understanding of sediment processes: this means that it is difficult to assess whether SWAT or InVEST is closer to reality, even if their spatial estimates of sediment export rates vary significantly (Fig. 4). Despite these challenges, monitoring data remain useful to provide current and local estimates of climate and sediment yields, as illustrated in the previous paragraph.

Third, related to model sophistication, our analyses provided mixed results, with InVEST and SWAT yielding different estimates of priority restoration areas, but generally consistent in terms of the effect of future scenarios (28%, 36%, or 42% change, depending on model resolution, see Section 3.2). These results should be interpreted in the light of several caveats. First, the InVEST model only represents annual sediment export. While this value can be compared to annual values simulated by SWAT, it does not provide much insight into the capacity of the model to represent watershed processes. On the other hand, previous SWAT analyses indicate that the model has a reasonable performance but important bias (e.g. 24% bias in TSS for validation data) and fails to include important non-linear effects (Fisher et al., 2018). This casts doubt on the ability of even the more sophisticated model, SWAT, to capture land-use change effects on watershed processes/sediment export. Our results add to the growing literature on ecosystem services model comparison (Bagstad et al., 2013; Ochoa and Urbina-Cardona, 2017; Vigerstol and Aukema, 2011) and call for additional efforts to systematize this type of research.

Finally, LULC data, and in particular their resolution, are also often a large source of uncertainty, leading teams to collect finer resolution and current data. In our study, we found that the finer data significantly improved the InVEST model outputs before calibration, although this seemed related to a model artifact (i.e. sensitivity to input resolution) rather the introduction of new information (Section 3.3).

4.3. Implications and future work

This study has several implications for future work in the region, which are in line with the recommendations on boundary work (Clark et al., 2016) and monitoring program guidance (Higgins and Zimmerling, 2013). We summarize the main ones as follows:

- Model sophistication does affect results, but there is little evidence that accurate estimates of sediment yields are needed to support the WPP. Rather, robust modeling approaches are needed to provide scientific credibility (e.g. providing several lines of evidence, such as multiple models and observed data),
- Without adequate calibration, it is difficult to develop credible sediment models, which means that attention should be paid to developing and maintaining monitoring programs,
- Monitoring programs should be simple but designed to increase model credibility: for example, deriving inputs such as erosivity data, which is a key input for many simple models, or assessing sediment export at multiple points in space or time,
- LULC data and its resolution significantly affect model results, suggesting that high-resolution LULC will be important in cases when information needs to be used instrumentally,
- Uncertainty in prioritizing areas for restoration with models means that scientific information should always be considered in combination with other approaches (e.g. participatory process),
- Similar studies of IWS programs, analyzing generation and use of hydrologic information, will help determine which findings are specific to the present case study and which ones can be generalized.

5. Conclusion

Our study illustrates that hydrologic information should be co-developed with information users (investors or project managers who *may* use the information and land holders who ideally are part of the planning process). We recommend: i) determining through interdisciplinary approaches and boundary work whether stakeholders will use outputs (and if so, how), and ii) developing appropriate models and monitoring programs. In the Camboriú WPP, the main role of science was to facilitate conversations, provide credibility, and demonstrate commitment to long-term evaluation procedures, so that the production of a minimum viable scientific product, such as the InVEST model, may have been sufficient to save resources for field work and implementation.

Author statement

Hamel: Conceptualization, Methodology, Software, Writing – Original Draft; Bremer: Conceptualization, Methodology, Investigation, Writing – Original Draft; Ponette-González: Formal Analysis, Writing – Review & Editing; Acosta: Software, Data Curation, Visualization; Fisher: Conceptualization, Writing – Review & Editing; Steele: Data Curation; Writing – Review & Editing; Cavassani: Investigation, Resources; Klemz: Investigation, Resources; Blainski: Resources, Data Curation; Brauman: Conceptualization, Writing – Review & Editing, Funding Acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

Table A1
Summary of InVEST and SWAT input data.

Input	Sources
Climate inputs	SWAT: Precipitation data from five weather stations (Fisher et al., 2018) including Louro station InVEST: Erosivity calculated from two sources: i) national average over the 1980–2013 period (Xavier et al., 2016), converted to erosivity with a relationship by Oliveira et al. (2012); ii) local hourly precipitation in 2016 (from Louro weather station), converted to erosivity following the methods described in Section 3.4 of the main text
Soil erodibility raster	Both models: Data provided by Santa Catarina state used in the SWAT model (Fisher et al., 2018)
Digital elevation model raster	Both models: 1 m data from Secretariado Desenvolvimento Econômico Sustentável (Fisher et al., 2018) InVEST: 1 m data resampled to 10 m and pit-filled in Qgis (Wang and Liu, 2006); 30 m data from SRTM and pit-filled.
LULC raster	Both models: 30 m data from Landsat8 SWAT: 1 m data obtained from Worldview 2 imagery (Fisher et al., 2018) InVEST: 10 m data resampled from the 1 m Worldview 2 data used in the SWAT model
C and P factors	Both models: literature values used in the SWAT model (Fisher et al.,2018)

Appendix B. Processing of climate and sediment monitoring data

Climate data

Annual erosivity was calculated with two alternative methods. First, we used a national dataset of average precipitation over 34 years, from 1980 to 2013 (Xavier et al., 2016) and converted annual precipitation to erosivity based on a linear relationship between annual erosivity and annual precipitation for 80 Brazilian cities (Oliveira et al., 2012).

Next, we used a local weather station (Louro) for 2016. Given the lack of sub-hourly data, erosivity was estimated using the EI_{60} index (D'Odorico et al., 2001). Rainfall erosivity (EI_{60}) for each erosive event was calculated as:

$$EI_{60} = \left(\sum_{r=1}^{k} e_{r*v_r} \right) I_{60}$$

where e_r is the rainfall kinetic energy (MJ ha^{-1} mm^{-1}) and v_r is the rainfall amount (mm) during the rth time interval of the rainfall event divided into k-parts. Erosive rainfall events were those with cumulative rainfall amounts ≥10 mm and separated from other events by a 6-hour dry period. Annual erosivity was estimated for 2016 by summing the individual EI_{60} values of erosive events. Because coarser resolution precipitation data provide lower estimates of rainfall erosivity (Yin et al., 2007), we applied an annual calibration factor of 1.5597 to the annual erosivity estimate (Panagos et al., 2016).

In 2016, total rainfall at the Louro climatic station was 1612 mm. During this period, there were 201 precipitation events with measurable precipitation (≥0.2 mm), of which 53 (26%) were erosive (≥10 mm). Approximately 1341 mm (83%) of total annual rainfall fell during these erosive rainfall events.

Sediment data

We calculated total suspended solids (TSS, mg L^{-1}) from water turbidity (NTU) measurements using the linear regression reported by Blainski et al. (2017) for the Camboriú watershed:

$$TSS = (0.8695 * NTU) + 66.849$$

Stream depth measurements (cm) were converted to water discharge (m^3 s^{-1}) using a rating curve developed for the Canoas watershed (Fisher et al., 2018).

$$Q = 0.0207 * (\text{stream depth} - 64.661)^{1.294}$$

Suspended sediment loads were calculated by multiplying TSS by water discharge and then converted to daily loads (t d^{-1}). Daily sediment yields were calculated by dividing by the Canoas watershed area (4800 ha). Because there were variable numbers of observations among years (214–248 days), mean daily sediment yield was multiplied by 365 days to obtain annual sediment yield (t ha^{-1} yr^{-1}) for each year of data.

There were 369 records of daily sediment yield from 2015 and 2016 with associated daily precipitation data. Only 112 days had total daily precipitation >1.27 mm, which we used as a minimum cutoff for our analysis of sediment yield against precipitation.

References

Adem Esmail, B., Geneletti, D., Albert, C., 2017. Boundary work for implementing adaptive management: a water sector application. Sci. Total Environ. 593–594, 274–285. https://doi.org/10.1016/j.scitotenv.2017.03.121.

ANA, 2012. Manual Operativo do Programa Produtor de Água. Agência Nacional de Águas, Brasilia, DF.

Bagstad, K.J., Semmens, D.J., Waage, S., Winthrop, R., 2013. A comparative assessment of decision-support tools for ecosystem services quantification and valuation. Ecosystem Services 5, 27–39. https://doi.org/10.1016/j.ecoser.2013.07.004.

Bennett, G., Carroll, N., 2014. Gaining Depth: State of Watershed Investment. Forest trends ecosystem marketplace, Washington, DC.

Blainski, É., Acosta Porras, Andrea, Pospissil, E. Hamilton, Garbossa, L., Pinheiro, A., 2017. Revista Brasileira de Recursos Hídricos Brazilian Journal of Water Resources Simulation of land use scenarios in the Camboriú River Basin using the SWAT model Simulação de cenários de uso e ocupação das terras na bacia hidrográfica do Rio Camboriú utiliza. Rev. Bras. Recur. Hidr. 22. https://doi.org/10.1590/2318-0331.011716110.

Bremer, L.L., Farley, K.A., Lopez-Carr, D., 2014. What factors influence participation in payment for ecosystem services programs? An evaluation of Ecuador's SocioPáramo program. Land Use Policy 36, 122–133. https://doi.org/10.1016/J.LANDUSEPOL.2013.08.002.

Bremer, L.L., Auerbach, D.A., Goldstein, J.H., Vogl, A.L., Shemie, D., Kroeger, T., Nelson, J.L., Benítez, S.P., Calvache, A., Guimarães, J., Herron, C., Higgins, J., Klemz, C., León, J., Sebastián Lozano, J., Moreno, P.H., Nuñez, F., Veiga, F., Tiepolo, G., 2016a. One size does not fit all: natural infrastructure investments within the Latin American Water Funds Partnership. Ecosystem Services 17, 217–236. https://doi.org/10.1016/j.ecoser.2015.12.006.

Bremer, L.L., Vogl, A.L., De Bièvre, B., Petry, P., 2016b. Bridging Theory and Practice for Hydrological Monitoring in Water Funds. Instituto de Ecología, A.C, Veracruz, MX.

Bremer, L.L., Brauman, K.A., Nelson, S., Prado, K.M., Wilburn, E., Fiorini, A.C.O., 2018. Relational values in evaluations of upstream social outcomes of watershed Payment for Ecosystem Services: a review. Curr. Opin. Environ. Sustain. 35, 116–123. https://doi.org/10.1016/j.cosust.2018.10.024.

Bremer, L.L., Hamel, P., Ponette-González, A., Pompeu, P., Saad, S., Brauman, K.A., 2019. Who are we measuring and modeling for? Supporting multi-level decision-making in watershed management. Water Resour. Res. (in review).

Bryant, B.P., Borsuk, M.E., Hamel, P., Oleson, K.L.L., Schulp, C.J.E., Willcock, S., 2018. Transparent and feasible uncertainty assessment adds value to applied ecosystem services modeling. Ecosystem Services 33, 103–109. https://doi.org/10.1016/j.ecoser.2018.09.001.

Cash, D. W., Clark, W. C., Alcock, F., Dickson, N. M., Eckley, N., Guston, D. H., Jäger, J., & Mitchell, R. B. (2003). Knowledge systems for sustainable development. Proc. Natl. Acad. Sci., 100(14), 8086 LP – 8091. https://doi.org/https://doi.org/10.1073/pnas.1231332100.

Chan, K.M.A., Anderson, E., Chapman, M., Jespersen, K., Olmsted, P., 2017. Payments for ecosystem services: rife with problems and potential—for transformation towards sustainability. Ecol. Econ. 140, 110–122. https://doi.org/10.1016/J.ECOLECON.2017.04.029.

Clark, W. C., Tomich, T. P., van Noordwijk, M., Guston, D., Catacutan, D., Dickson, N. M., & McNie, E. (2016). Boundary work for sustainable development: natural resource management at the Consultative Group on International Agricultural Research (CGIAR). Proc. Natl. Acad. Sci., 113(17), 4615 LP – 4622. https://doi.org/https://doi.org/10.1073/pnas.0900231108.

D'Odorico, P., Yoo, J.C., Over, T.M., 2001. An assessment of ENSO-induced patterns of rainfall erosivity in the Southwestern United States. J. Clim. 14 (21), 4230–4242 (https://doi.org/10.1175/1520-0442(2001)014<4230:AAOEIP>2.0.CO;2).

Farley, K.A., Anderson, W.G., Bremer, L.L., Harden, C.P., 2011. Compensation for ecosystem services: an evaluation of efforts to achieve conservation and development in Ecuadorian páramo grasslands. Environ. Conserv. 38 (4), 393–405. https://doi.org/10.1017/S037689291100049X.

Figueroa, F., Caro-Borrero, Á., Revollo-Fernández, D., Merino, L., Almeida-Leñero, L., Paré, L., Espinosa, D., Mazari-Hiriart, M., 2016. "I like to conserve the forest, but I also like the cash". Socioeconomic factors influencing the motivation to be engaged in the Mexican Payment for Environmental Services Programme. J. For. Econ. 22, 36–51. https://doi.org/10.1016/J.JFE.2015.11.002.

Fisher, J.R.B., Acosta, E.A., Dennedy-Frank, P.J., Kroeger, T., Boucher, T.M., 2018. Impact of satellite imagery spatial resolution on land use classification accuracy and modeled water quality. Remote Sensing in Ecology and Conservation 4 (2), 137–149. https://doi.org/10.1002/rse2.61.

Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S.P., Quintero, M., 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: a systematic review. J. Hydrol. 535, 625–636. https://doi.org/10.1016/j.jhydrol.2016.01.034.

Guswa, A.J., Brauman, K.A., Brown, C., Hamel, P., Keeler, B.L., Sayre, S.S., 2014. Ecosystem services: challenges and opportunities for hydrologic modeling to support decision making. Water Resour. Res. 50 (5). https://doi.org/10.1002/2014WR015497.

Hamel, P., Chaplin-Kramer, R., Sim, S., Mueller, C., 2015. A new approach to modeling the sediment retention service (InVEST 3.0): case study of the Cape Fear catchment, North Carolina, USA. Sci. Total Environ. 524–525. https://doi.org/10.1016/j.scitotenv.2015.04.027.

Hamel, P., Falinski, K., Sharp, R., Auerbach, D.A., Sánchez-Canales, M., Dennedy-Frank, P.J., 2017. Sediment delivery modeling in practice: comparing the effects of watershed characteristics and data resolution across hydroclimatic regions. Sci. Total Environ. 580. https://doi.org/10.1016/j.scitotenv.2016.12.103.

Hamel, P., Riveros-Iregui, D., Ballari, D., Browning, T., Célleri, R., Chandler, D., Chun, K.P., Destouni, G., Jacobs, S., Jasechko, S., Johnson, M., Krishnaswamy, J., Poca, M., Pompeu, P.V., Rocha, H., 2018. Watershed services in the humid tropics: opportunities from recent advances in ecohydrology. Ecohydrology 11 (3). https://doi.org/10.1002/eco.1921.

Heink, U., Marquard, E., Heubach, K., Jax, K., Kugel, C., Neßhöver, C., Neumann, R.K., Paulsch, A., Tilch, S., Timaeus, J., Vandewalle, M., 2015. Conceptualizing credibility, relevance and legitimacy for evaluating the effectiveness of science–policy interfaces: challenges and opportunities. Sci. Public Policy 42 (5), 676–689. https://doi.org/10.1093/scipol/scu082.

Higgins, J.V., Zimmerling, A., 2013. A Primer for Monitoring Water Funds. The Nature Conservancy, Arlington, VA.

Klemz, C., Petry, P., Kroeger, T., Acosta, E.A., Blainski, E., Garbossa, L.H.P., Cavassani, A.T., Dacol, K.C., Comparim, R., Bremer, L.L., 2016. Case study 4: Camboriú, Brazil. In: Bremer, L.L., Vogl, A.L., De Bièvre, B., Petry, P. (Eds.), Bridging Theory and Practice for Hydrological Monitoring in Water Funds, p. 98.

Kolinjivadi, V., Hecken, G.Van, Francisco, D., Rodrı, J.C., 2017. As a lock to a key? Why science is more than just an instrument to pay for nature's services. Current Opinions in Environmental Sustainability (February), 1–6 https://doi.org/10.1016/j.cosust.2016.12.004.

Kroeger, T., Klemz, C., Boucher, T., Fisher, J.R.B., Acosta, E., Targa, A., Dennedy-frank, P.J., Garbossa, L., Blainski, E., Comparim, R., Giberti, S., Petry, P., Shemie, D., Dacol, K., 2019. Returns on investment in watershed conservation: application of a best practices analytical framework to the Rio Camboriú Water Producer. Sci. Total Environ. 657, 1368–1381. https://doi.org/10.1016/j.scitotenv.2018.12.116.

McKenzie, E., Posner, S., Tillmann, P., Bernhardt, J.R., Howard, K., Rosenthal, A., 2014. Understanding the use of ecosystem service knowledge in decision making: lessons from international experiences of spatial planning. Environment and Planning C: Government and Policy 32 (2), 320–340. https://doi.org/10.1068/c12292j.

Murdoch, W., Polasky, S., Wilson, K.A., Possingham, H.P., Kareiva, P., Shaw, R., 2007. Maximizing return on investment in conservation. Biol. Conserv. 139 (3), 375–388. https://doi.org/10.1016/j.biocon.2007.07.011.

Naeem, S., Ingram, J.C., Varga, A., Agardy, T., Barten, P., Bennett, G., ... Wunder, S., 2015. Get the science right when paying for nature's services. Science 347 (6227), 1206–1207.

Ochoa, V., Urbina-Cardona, N., 2017. Tools for spatially modeling ecosystem services: publication trends, conceptual reflections and future challenges. Ecosystem Services 26, 155–169. https://doi.org/10.1016/j.ecoser.2017.06.011.

Oliveira, P.T.S., Wendland, E., Nearing, M.A., 2013. Rainfall erosivity in Brazil: a review. CATENA 100, 139–147. https://doi.org/10.1016/j.catena.2012.08.006.

Panagos, P., Borrelli, P., Spinoni, J., Ballabio, C., Meusburger, K., Beguería, S., Klik, A., Michaelides, S., Petan, S., Hrabalíková, M., Olsen, P., Aalto, J., Lakatos, M., Rymszewicz, A., Dumitrescu, A., Perčec Tadić, M., Diodato, N., Kostalova, J., Rousseva, S., Banasik, K., Alewell, C., 2016. Monthly rainfall erosivity: conversion factors for different time resolutions and regional assessments. Water 8. https://doi.org/10.3390/w8040119.

Pattanayak, S.K., Wunder, S., Ferraro, P.J., 2010. Show me the money: do payments supply environmental services in developing countries? Rev. Environ. Econ. Policy 4 (2), 254–274. https://doi.org/10.1093/reep/req006.

Ponette-González, A.G., Marín-Spiotta, E., Brauman, K.A., Farley, K.A., Weathers, K.C., Young, K.R., 2013. Hydrologic connectivity in the high-elevation tropics: heterogeneous responses to land change. BioScience 64 (2), 92–104. https://doi.org/10.1093/biosci/bit013.

Ponette-González, A.G., Brauman, K.A., Marín-Spiotta, E., Farley, K.A., Weathers, K.C., Young, K.R., Curran, L.M., 2015. Managing water services in tropical regions: from land cover proxies to hydrologic fluxes. Ambio 44 (5), 367–375. https://doi.org/10.1007/s13280-014-0578-8.

Posner, S., Verutes, G., Koh, I., Denu, D., Ricketts, T., 2016. Global use of ecosystem service models. Ecosystem Services 17, 131–141. https://doi.org/10.1016/j.ecoser.2015.12.003.

Richards, R.C., Rerolle, J., Aronson, J., Pereira, P.H., Gonçalves, H., Brancalion, P.H.S., 2015. Governing a pioneer program on payment for watershed services: stakeholder involvement, legal frameworks and early lessons from the Atlantic forest of Brazil. Ecosystem Services 16, 23–32. https://doi.org/10.1016/j.ecoser.2015.09.002.

Salzman, J., Bennett, G., Carroll, N., Goldstein, A., Jenkins, M., 2018. The global status and trends of Payments for Ecosystem Services. Nature Sustainability 1 (3), 136–144. https://doi.org/10.1038/s41893-018-0033-0.

Santos de Lima, L., Ramos Barón, P. A., Villamayor-Tomas, S., & Krueger, T. (2019). Will PES schemes survive in the long-term without evidence of their effectiveness? Exploring four water-related cases in Colombia. Ecol. Econ., 156, 211–223. https://doi.org/https://doi.org/10.1016/j.ecolecon.2018.09.005.

Shapiro-Garza, E., 2013a. Contesting market-based conservation: payments for ecosystem services as a surface of engagement for rural social movements in Mexico. Hum. Geogr. 6 (1), 134–150.

Shapiro-Garza, E., 2013b. Contesting the market-based nature of Mexico's national payments for ecosystem services programs: four sites of articulation and hybridization. Geoforum 46, 5–15. https://doi.org/10.1016/J.GEOFORUM.2012.11.018.

Sharps, K., Masante, D., Thomas, A., Jackson, B., Redhead, J., May, L., Prosser, H., Cosby, B., Emmett, B., Jones, L., 2017a. Comparing strengths and weaknesses of three ecosystem services modelling tools in a diverse UK river catchment. Sci. Total Environ. 584–585, 118–130. https://doi.org/10.1016/j.scitotenv.2016.12.160.

Sharp, R.S., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Nelson, E., Ennaanay, D., Wolny, S., Olwero, N., Vigerstol, K., Pennington, D., Mendoza, G., Aukema, J., Foster, J., Forrest, J., Cameron, D., Arkema, K., Lonsdorf, E., Kennedy, C., Verutes, G., Kim, C.K., Guannel, G., Papenfus, M., Toft, J., Marsik, M., Bernhardt, J., Griffin, R., Glowinski, K., Chaumont, N., Perelman, A., Lacayo, M., Mandle, L., Hamel, P., Chaplin-Kramer, R., 2017b. InVEST 3.6 User's Guide. http://releases.naturalcapitalproject.org/invest-userguide/latest/.

Taffarello, D., Calijuri, M. do C., Viani, R.A.G., Marengo, J.A., Mendiondo, E.M., 2017. Hydrological services in the Atlantic Forest, Brazil: an ecosystem-based adaptation using ecohydrological monitoring. Climate Services 8, 1–16. https://doi.org/10.1016/J.CLISER.2017.10.005.

de Vente, J., Poesen, J., 2005. Predicting soil erosion and sediment yield at the basin scale: scale issues and semi-quantitative models. Earth Sci. Rev. 71 (1–2), 95–125. https://doi.org/10.1016/j.earscirev.2005.02.002.

de Vente, J., Poesen, J., Verstraeten, G., Govers, G., Vanmaercke, M., Van Rompaey, A., Arabkhedri, M., Boix-Fayos, C., 2013. Predicting soil erosion and sediment yield at regional scales: where do we stand? Earth Sci. Rev. 127, 16–29. https://doi.org/10.1016/j.earscirev.2013.08.014.

Vigerstol, K.L., Aukema, J.E., 2011. A comparison of tools for modeling freshwater ecosystem services. J. Environ. Manag. 92 (10), 2403–2409. https://doi.org/10.1016/j.jenvman.2011.06.040.

Vogl, A.L., Goldstein, J.H., Daily, G.C., Vira, B., Bremer, L.L., McDonald, R.I., Shemie, D., Tellman, B., Cassin, J., 2017. Mainstreaming investments in watershed services to enhance water security: barriers and opportunities. Environ. Sci. Pol. 75, 19–27. https://doi.org/10.1016/j.envsci.2017.05.007.

Wang, L., Liu, H., 2006. An efficient method for identifying and filling surface depressions in digital elevation models for hydrologic analysis and modelling. Int. J. Geogr. Inf. Sci. 20 (2), 193–213. https://doi.org/10.1080/13658810500433453.

Wilburn, E., Bremer, L.L., Brauman, K.A., Gould, R., Seehusen, S., Prado, K.A., Hamel, P., 2017. Voices from the field: participant perspective on growth and sustainability opportunities for water producer projects. Retrieved from. https://naturalcapitalproject.stanford.edu/wp-content/uploads/2018/01/VoicesFromTheField_Eng.pdf.

Wunder, S., 2005. Payments for Environmental Services: Some Nuts and Bolts. Occasional Paper No. 42. Center for International Forestry Research Retrieved from. https://hdl.handle.net/10568/19193.

Xavier, A. C., King, C. W., & Scanlon, B. R. (2016). Daily gridded meteorological variables in Brazil (1980–2013). Int. J. Climatol., 36(6), 2644–2659. https://doi.org/https://doi.org/10.1002/joc.4518.

Yin, S., Xie, Y., Nearing, M.A., Wang, C., 2007. Estimation of rainfall erosivity using 5- to 60-minute fixed-interval rainfall data from China. CATENA 70 (3), 306–312. https://doi.org/10.1016/j.catena.2006.10.011.