HYDROLOGICAL FORECASTING WITH HEC-RTS: CASE STUDY OF BOI RIVER TRAIL, SOUTHERN BRAZIL

PREVISÃO HIDROLÓGICA COM HEC-RTS: ESTUDO DE CASO DA TRILHA DO RIO BOI, SUL DO BRASIL

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Introduction

Floods are extreme hydrological events, and worldwide they are associated with the most common type of disaster, accounting for 44% of total disasters that occurred in the world between 2000 and 2019 (UNDRR; CRED, 2020). According to the disasters global database Emergency Disasters Database (EM-DAT) (https://public.emdat.be/), 72 floods and 2482 deaths were recorded in Brazil between 2000 and 2019 (EM-DAT, 2022). Hence, national and local disaster risk reduction strategies must be urgently aligned with the Sendai Framework for Disaster Risk Reduction, whose main goals are the substantial reduction of mortality, affected people, and losses and damages related to disasters by 2030 (UNDRR, 2015).

Overall, interactions between natural hazards and socio-technological vulnerabilities result in negative impacts much more in urban areas than in rural areas. This fact can be attributed to the developed areas, which increase population density, often, in high hazard areas. Hence, the population density in urban areas is bigger than in rural areas, raising the level of disaster risk because more people are exposed to the potential hazards. However, losses and damages due to interactions between humans and water systems also occur in rural areas and environmentally-preserved places where visitors (tourists) stay.

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The Brazilian biogeodiversity is attractive for the ecotourism which has been increasing particularly in many developing countries since the 1990s. In Brazil, more than 15 million tourists visited 137 environmentally protected areas in 2019, an increase of 20.4% compared to 2018, being 6.4% due to the real increase in visits and 14% due to the improvement in the monitoring effort (ICMBIO, 2020). Despite the well-being and other benefits for the tourists promoted by proximity with nature, more people are exposed to potential hazards. For instance, while hiking, tourists who need to cross a river can be surprised by the high velocities in the water flow. Focusing on hydrological hazards, people under hydraulic conditions of water depth, flow velocities, or the combination of both can suffer from partial or complete loss of balance and stability and, consequently, will be swept away by the runoff force (STEPHENSON, 2002; MARTÍNEZ-GOMARÍZ et al., 2016; MONTEIRO et al., 2021).

In disaster risk management, structural and non-structural measures can be used for reducing negative impacts due to floods. Structural measures are any physical infrastructure or application of engineering techniques, while non-structural measures involve knowledge, practice, or agreement to reduce risks and impacts, in particular through policies and laws, public awareness-raising, training, and education (UNDRR, 2009). An example of a non-structural measure is the early warning system, which aims to generate and disseminate meaningful warning information to enable the population threatened by a hazard to prepare and to act appropriately and in time to reduce the possibility of harm or loss (UNDRR, 2009). To perform this measure, hydrological forecasting is a relevant technique for translating meteorological observations and forecasts into estimates of river flows (SENE, 2010). Hence, hydrological forecasting inserted into an early warning system can be used for reducing hydrological risks in any social activities including ecotourism practices.

Concerning the Sendai Framework goals, the increase of ecotourism practice, and the hydrological hazards in protected areas, it is very important to discuss strategies for reducing risks in natural places, especially in rivers. With this in mind, in this study, our main objective was to propose a hydrological forecasting system for a river in a natural place, where visitors need to cross a river. First, we present general concepts about hydrological forecasting by responding to the following questions: "*What is it?*", "*Why is its application useful?*", "*How is it done?*", and "*What tools can we use to do it?*". Next, we describe relevant software that can be used for supporting hydrological forecasting. And, finally, we demonstrate one case study in the Boi River Trail, which is one of the most famous ecotourism points in Brazil, where various harms to tourists due to extreme hydrological events have been frequently reported. This case study confirms the importance of risk management related to ecotourism.

Hydrological forecast – Concepts

What is hydrological forecasting?

Hydrological forecasting can be defined as a technique capable of providing information on the water level or discharge that will pass at a certain point in a watercourse with a certain advance in time (TUCCI; COLLISCHONN, 2003; FAN *et al.,* 2016). Hydrological forecasting can be performed to predict future discharge characteristics not only of rivers, but also of lakes, reservoirs, and other waterbodies (BORSCH *et al.,* 2018).

In other words, based on a given rainfall event that occurrs in a watershed, the hydrological forecasting aims to estimate what will be the variation in discharge or water level at a given point in a watercourse and how long it will take for a floodwave to reach a certain location. Furthermore, the forecast results are not necessarily unique, i.e., forecasts based on different methods or different input data will result in discharges with different magnitudes. In the present study, we focus on the hydrological forecast of floods. However, forecasts can be applied also for other purposes such as forecasting droughts or soil moisture. Figure 1 presents the hydrological forecast scheme. A society often needs to know the future discharges at a certain point along a river. This need is very similar to that of weather forecasting.

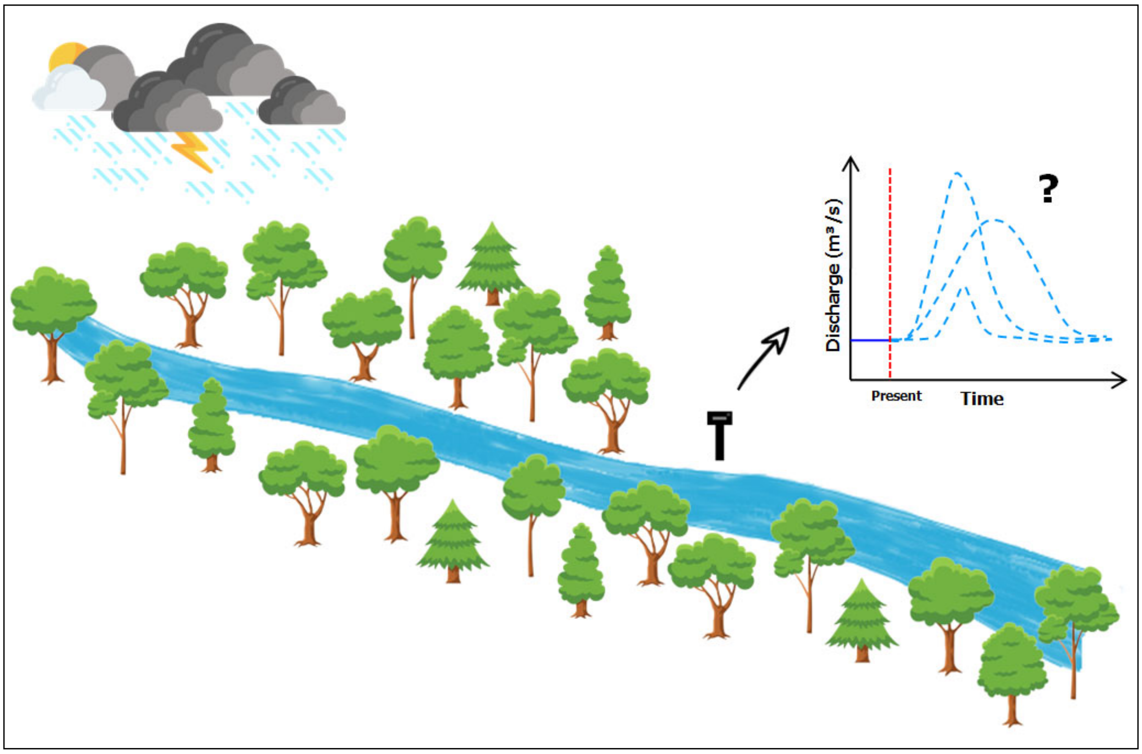


Figure 1. Representative scheme of hydrological forecasting.

In terms of time interval, forecasts can be classified into five categories: i) very short term (or nowcasting - advance of up to 6 hours); ii) short term (up to 3 days); iii) medium term (up to 10 days); iv) sub-seasonal (up to 45 days); and v) long term (from 2 to 6 months) (COLLISCHONN et al., 2005; MELLER, 2012). The longer this inerval, the greater are the uncertainties of the obtained results.

The hydrometeorological data required to develop a forecast includes real-time river conditions, precipitation data, and meteorological forecasts. A flood early warning system could incorporate all or some of these data in order to increase warning time to the potentially impacted populations. The type of data used (hydrologic, precipitation, or forecasts) will impact this lead time available for the warning. However, the type of data will also impact the uncertainty of the warning. As shown in Figure 2, the longer the lead time provided, the higher the uncertainty of the warning to produce false positives (unnecessary evacuations or closures of facilities, for example). Therefore, no one system will be appropriate for all situations, and this is an important reason to develop a planning study associated with a proposed flood early warning system.

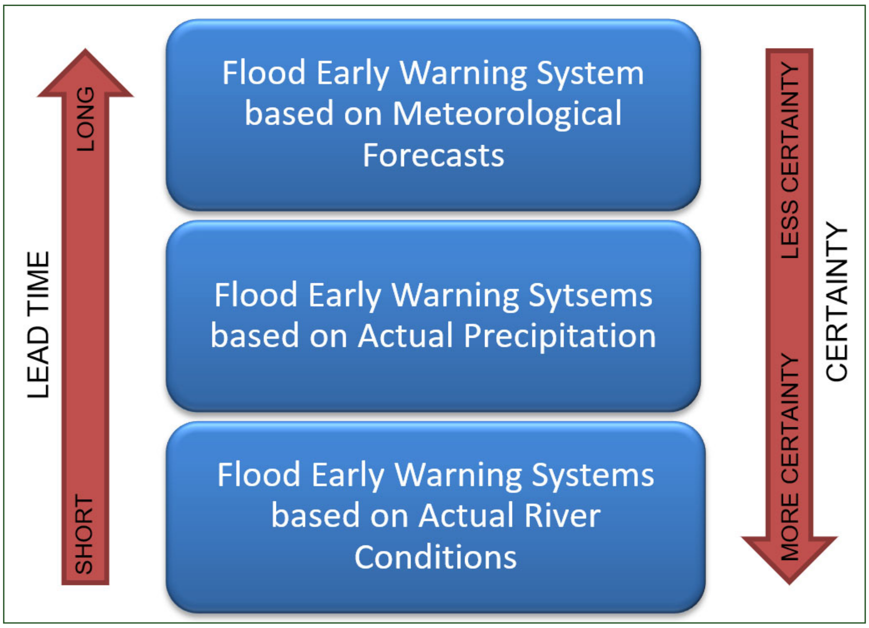


Figure 2. Inverse Relationship between Lead Time and Certainty for Various Types of Flood Early Warning Systems.

Why is its application useful?

The results obtained from the hydrological forecasts can have diverse applications. In general, most of the forecasting systems in operation are intended to support river-reservoir system management where reservoirs serve for hydroelectric generation and/or drinking-water supply. Furthermore, such forecasts are a basis for flood alert emissions in urban areas (FAN et al., 2015).

Specifically in case of their application to the warning systems development, hydrological forecasts can be considered very important to support the water resources management and to assist in decision-making by public managers, because they allow monitoring hydrological events and estimating their magnitude in order to anticipate possible consequences (FAN, 2015; WANDERS et al., 2019).

In Brazil, the use of hydrological forecasting systems to control and minimize the floods' consequences is mainly done through the Critical Events Alert System (SACE), which is maintained by the Geological Survey of Brazil (CPRM). Currently, the SACE has operational monitoring systems for 16 Brazilian watersheds with drainage areas ranging from 4,100 km² to 2,100,000 km² and is in the implementation phase for the São Francisco River watershed (CPRM, 2022). In this sense, it is worth noting that most of all the warning systems that are currently in operation are for controlling and mitigating the floods impacts in large watersheds. Outside Brazil, many of the operating systems that stand out are also applied on a national or continental scale, such as the Hydrological Forecasting System (HyFS) in Australia and the European Flood Alert System (EFAS).

For small watersheds whose area is less than 100 km² (SILVEIRA; TUCCI, 1998), a few forecasting systems are in operation, and the development research related to these systems for small watersheds is also more scarce in Brazil as well as the rest of the world. According to Gaborit et al. (2014) and Burkard et al. (2018), the implementation and operation of forecasting systems in small watersheds are hampered mainly due to the large uncertainties in the predicted rainfall data. Furthermore, the small watersheds respond very quickly to intense rainfall events are are more susceptable to smaller cells of convective storms, which are more difficult to predict. This makes forecasting the hydrology in smaller basins more complex and complicated.

In Brazil, the forecast in small watersheds is still more difficult due to the fact that the hydrometeorological monitoring system is carried out typically for larger watersheds, which often makes it impractical to obtain data for the small-scale simulations. Hence, not only in Brazil but also in the rest of the world, flood forecasting systems applied to small watersheds are scarcer than for large and medium-sized basins (FREUDENTHALER; STUMPTNER, 2015).

In addition, the application of forecasting and warning systems for floods management is done normally in urban areas, while similar applications are very scarce in rural areas or natural environments. With the growing demand for ecotourism activities in recent years, especially trails or other activities close to water courses (MAZZALI et al., 2021), the number of occurrences of emergency situations due to drowning with rapid changes in water discharge has been increasing. Therefore, the development of hydrological forecasting systems in these places should be considered as an important tool for the disaster risk managers.

How is hydrological forecasting done?

The development of a hydrological forecasting system to determine the future discharge or water level in a rivers is an important challenge. Difficulties in developing an effective forecasting system is due to the fact that the phenomena that govern the hydrometeorological dynamics possess chaotic, non-linear and complex natures (YASSEN et al., 2016).

In general, as fundamental input data for carrying out a hydrological forecast, we use historical records of rainfall, measured data of discharge and water level as well as information on the physical characteristics of the analyzed watershed. Based on these data, discharge within this watershed can be estimated in response to a given rainfall event.

According to Tucci (1998), the main techniques used to perform short-term discharge forecasting can be summarized in the following categories: i) forecasting based on information on the water level or discharge of the river upstream; ii) forecasting from rainfall estimations with radar and/or telemetric networks of rainfall gauges integrated into a rainfall-discharge model; and iii) meteorological (rainfall) forecasting coupled to a rainfall-discharge model.

Depending on the objectives to be achieved, the watershed size, the required antecedent time and the available hydrometeorological information, the forecasting can be performed by using one of the above-mentioned methods (FAN, 2015; SIQUEIRA et al., 2016). Some of them are simpler, based only on water level or discharge data obtained at an upstream point. In these methods, flow propagation theory allows determining the time necessary for a flood wave to travel downstream to a point of interest. This approach provides more certainty in the forecast predictions, but will provide less lead time in the forecast. On the other hand, there are more complex approaches in which a hydrological model is coupled to a hydrodynamic model to make predictions. Each method has its advantages, limitations and associated uncertainties (BARTHOLMES; TODINI, 2005).

Here, it is important to comment that, among the above-mentioned techniques, the simplest ones using less input data are capable to provide forecasting with shorter antecedent time. In the case that more data like forecasted rainfall estimates is entered as input data, longer forecast horizons would be obtained. However, this type of situation usually increases the uncertainties associated with the obtained results.

Furthermore it should be highlighted that currently many hydrological forecasting systems use as input data the ensemble rainfall estimates. Deterministic forecasting normally uses only a set of input data from meteorological models, and generates a single trajectory for future discharge values at a certain point in a river. While, probabilistic forecasting, which is based on ensemble rainfall estimates, uses not only an initial condition as input data of meteorological models, but also several slightly-disturbed initial conditions and/or different meteorological models that allow portraying the possible scenarios of occurrence of a given event. Thus, the uncertainties associated with the generated results are taken into account and a probability of occurrence of a given event is considered.

What tools are used for hydrological forecasting?

When a user obtains the input data and defines one technique for hydrological forecasting, a series of calculations must be performed in order to determine the discharge and/or the water level that will pass at a certain point along a river at a specific time. In this context, there are several computational models and tools that support the development of hydrological forecasting systems. Among them, there are the MGB (Large Basin Model), the Tank Model, the LISFLOOD, the TOPMODEL (Topography based hydrological model), the HEC-RTS (Hydrologic Engineering Center - Real Time Simulation), among others.

We focus here on the analysis of the HEC-RTS (USACE-HEC, 2020), which is a program that was developed by the United States Army Corps of Engineers (USACE). In this chapter, we adopted this model aiming to develop a forecasting system of a basin with ecoturism activities.

Hydrologic Engineering Center - Real Time Simulation (HEC-RTS)

Before presenting the functionalities of HEC-RTS in more detail, we briefly present a history of USACE, which is the entity responsible for this software development. We present other softwares that are applied together with the HEC-RTS to carry out hydrological forecasting and also ones related to water resources management and consequently disaster risk management.

Brief history of USACE

The USACE history began in 1775 when the US Predident George Washington appointed the Army's first engineering officers. These engineers served in combat in all subsequent American wars. However, it was only in 1802 that the US Army created a separate and permanent Corps of Engineers. Since then, USACE has contributed to both military construction and civil works, playing a key role in the country's development. Among the works carried out throughout the 19th century, the construction of coastal fortifications, jetties and navigation channels can be highlighted.

After the occurrence of a sequence of floods between 1912 and 1927 in the lower Mississippi River Watershed, which resulted in several deaths and much destruction, a Flood Control Act was drafted in 1928, and its implementation was brought under control of USACE. An update of this law in 1936 made flood control an activity of the federal government.

Thus, in the 20th century, USACE became the main federal flood control agency in the United States. As a result, its role in responding to natural disasters has also grown significantly. It is worth noting that USACE assists in the management not only of flood-related disasters but also of disasters such as earthquakes and volcanic eruptions. However, here, we are going to focus on the management of disasters related to water resources.

Although USACE is in principle an engineering and construction organization, it has been historically committed to conducting research and development. This is extremely important, because water resources management requires continual improvement of knowledge and investment in new technologies.

In this regard, the US Army Corps of Engineers, Institute for Water Resources – Hydrological Engineering Center (CEIWR-HEC) was formed in 1964 to institutionalize technical knowledge related to water resources management. This center emerged from the need to perpetuate the knowledge of USACE engineers that was acquired over several years of work. Since many engineers were about to reach retirement age, there was concern that their experience would be lost and recovery would be difficult.

Thus, over the years CEIWR-HEC has organized and conducted training courses and initiated the development of the CEIWR-HEC water resources management software family. The first software packages developed by them were HEC-1 (watershed hydrology), HEC-2 (river hydraulics), HEC-5 (reservoir analysis for conservation) and HEC-4 (stochastic streamflow generation program).

Currently, this software family consists of more than twenty programs, some of which are known worldwide and are available for free download. Among the most popularly-used ones, the HEC-HMS (originally HEC-1), the HEC-RAS (originally HEC-2) and the HEC-ResSim (originally HEC-5) can be mentioned. In addition, the USACE has operationally applied some of these softwares, such as the Corps Water Management System (CWMS), which is a real-time hydrological forecasting system that supports decision-making and is used 24 hours a day, 7 days a week, to exercise water resources management and hydrological disaster prevention in the United States.

Principal softwares developed by USACE

As mentioned above, USACE has developed a series of software that can be used to assist in water resources management. Table 1 demonstrates the software developed by this institution and a brief description of each one.

Table 1. Software useful for water resources management, developed by USACE.

Acronym	Name	Description
CWMS	Corps Water Management System	It is a USACE exclusive hydrological forecasting system. It allows the management and processing of hydrometeorological data, providing as a response information related to the various characteristics of the flow. In this way, it assists in real-time decision making by water managers.
HEC-DSS	Data Storage System	It is a software designed to serve as a database to store and organize input and output data from other CEIWR-HEC software.
HEC-EFM	Ecosystem Functions Model	It assists in determining ecosystem responses to changes in the flow regime of a river or connected wetland.
HEC-GridUtil	Grid Utility Program	It is designed to visualize, process and analyze grid format data that is stored in HEC-DSS format.
HEC-FDA	Flood Damage Reduction Analysis	It performs integrated hydrological analysis and economic analysis. In addition, it assists in the use of risk analysis procedures to formulate and evaluate flood risk management measures.
HEC-FIA	Flood Impact Analysis	It helps to identify the consequences of flood events, in terms of economic (structures), agricultural and life losses.
HEC-HMS	Hydrologic Modeling System	It is a hydrological model designed to simulate the transformation processes of rain into flow for dendritic watersheds.
HEC-MetVue	Meteorological Visualization Utility Engine	Developed for the purpose of visualizing and manipulating meteorological datasets and for performing a variety of calculations and analysis, including temporal and spatial aggregation of datasets.
HEC-RAS	River Analysis System	It is a hydrodynamic model that performs steady and unsteady flow simulations in 1D or 2D. In addition, it is capable of simulating sediment transport, temperature modeling and water quality analyses.
HEC-ResSim	Reservoir System Simulation	It simulates reservoir operations in order to reduce flooding, assist in urban supply management and as a support for real-time decision making.
HEC-RPT	Regime Prescription Tool	This software aims to improve communication in working groups, produces recommendations and disseminates them in real time and makes hydrological information more accessible to water managers.
HEC-RTS	Real Time Simulation	It is a hydrological forecasting system that allows the acquisition, visualization and processing of hydrometeorological data. It also discloses the results obtained so that they serve as support for decision-making in real time.
HEC-WAT	Watershed Analysis Tool	It is a model integration tool that allows multidisciplinary teams at USACE offices to conduct water resource studies.

In addition to the software mentioned in Table 1, there are also HEC-GeoEFM, HEC-GeoHMS and HEC-GeoRAS which are extensions of HEC-EFM, HEC-HMS and HEC-RAS, respectively. Those extensions are used within ArcMap, and serve to facilitate the processing of geospatial data that are used as input information in the application of the "base" software.

The descriptions of the software presented in Table 1 make it clear that their functionalities allow performing an integrated management of watersheds and water resources in general. In this sense, one of the great advantages of the software developed by USACE is that most of them are available for free download. In addition, the user manuals that accompany these programs are very didactic. In the case of the HEC-HMS and HEC-RAS which are used world-wide, there are several bibliographic materials that help in their application, even in non-English languages, for example, in Portuguese, Monteiro, Kobiyama and Zambrano (2015).

HEC-RTS

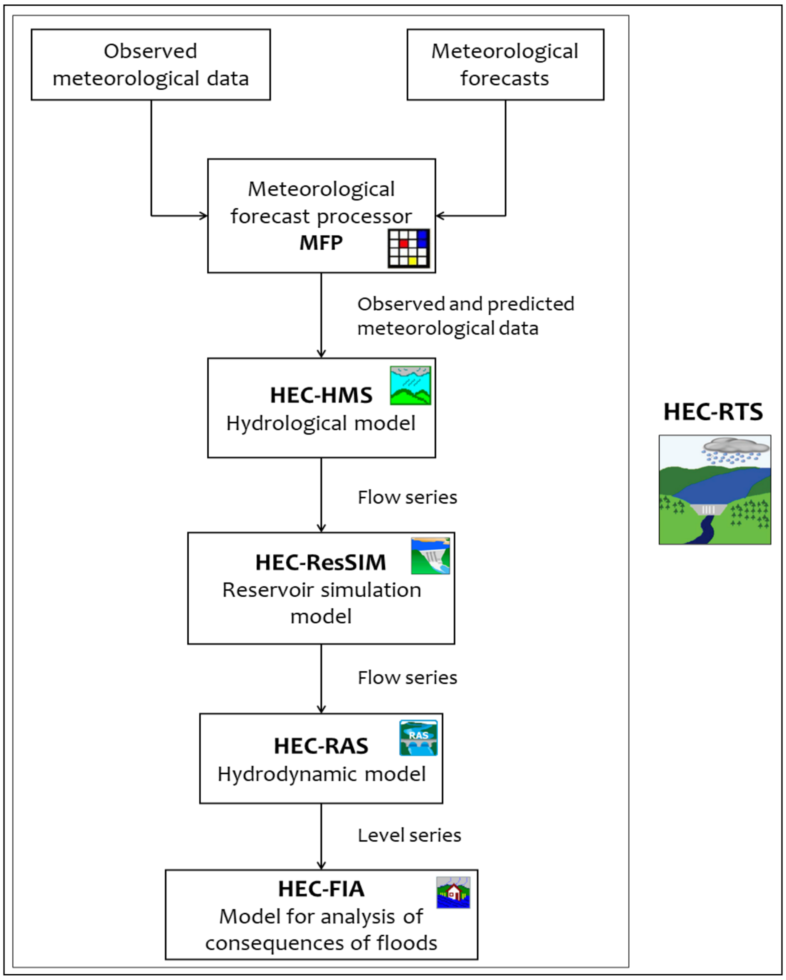
HEC-RTS is a relatively new software that was developed by USACE with the purpose of assisting in the management of water resources and facilitating real-time decision making (USACE-HEC, 2020). This software permits all the management of the data necessary for hydrological forecasting, from the acquisition and processing of input data to the dissemination of the obtained results for the population.

It is characterized by being the public version of another software for internal use by USACE, which is the Corps Water Management System (CWMS). The difference between CWMS and HEC-RTS is the operating system on which the program is based. While CWMS uses Oracle database, HEC-RTS uses Windows.

For the HEC-RTS application, it is necessary to use together other software that were developed by the USACE, among which include the Meteorological Forecast Processor (MFP), HEC-MetVue, HEC-HMS, HEC-ResSIM, HEC-RAS and HEC-FIA. As mentioned above, each of these programs can be operated separately. However, in HEC-RTS these softwares are combined to provide a comprehensive forecasting for a watershed, providing results ranging from data on discharge volumes to actions that can be taken to mitigate the impacts of events (CHARLEY, 2010). In this way, the role of HEC-RTS is to facilitate the exchange of data among these softwares so that the information flow is continuous and faster during forecasting process.

For example, if a user wants to estimate the extent of a flood event resulting from a forecasted rainfall, the HEC-HMS could first be used separately to analyze the maximum discharges. Afterwards, the output hydrographs could be entered as input data in the HEC-RAS to assess the areas flooded by this event. On the other hand, in case of HEC-RTS, this process will be carried out more easily. A user just simply inserts the calibrated hydrological and hydrodynamic models into the HEC-RTS, and inserts the forecasted rainfall estimates, and then the exchange of information between the HEC-HMS and the HEC-RAS will take place automatically. This helps in the watershed management and facilitates decision making.

Figure 3 shows a flowchart of data exchanges carried out among the models within the HEC-RTS. In this flowchart, all the tools available for use are included. However, it is worth mentioning that, in order to use the HEC-RTS, there is no need to apply all these software to make a forecasting. The software that will be applied and the order in which they will be operated depend strongly upon the objectives and applications of the analysis being carried out (CHARLEY, 2010).



Source: Adapted from USACE-HEC (2020).

Figure 3. Functioning flowchartof a forecasting system in HEC-RTS. Note that all the software available for use is represented.

In this way, the information necessary to carry out the analyzes in the HEC-RTS are the input data for the execution of the other software (HEC-HMS, HEC-RAS, HEC-FIA, etc.) and comprise data related to the environmental conditions at the site, such as air temperature, evaporation and rainfall rate, predicted rainfall data, topographic data, and information regarding the consequences of possibly-taken decisions (USACE-HEC, 2020).

In addition, for a better forecasting, it is also recommended to have rainfall and discharge data for a few days before the analysis period ("lookback period") in order to assess the condition of the watersheds at the beginning of the forecasting. Then, the predictions provide data as similar to reality as possible. The definition of the time required for the lookback period varies according to the physical characteristics of the watershed, such as its drainage area and the soil type.

Thus, we can make forecasts considering different scenarios for short and medium term periods of time (CHARLEY, 2010). The results obtained from the forecasts provide managers information regarding the probability of occurrence of certain discharge thresholds quickly. This is extremely important in the management of extreme hydrological events, because it allows estimating their magnitude in order to minimize negative impacts.

However, as it is a relatively new software, there are not many studies that used HEC-RTS as a basis for the development of forecasting systems at this moment. Nevertheless, it is very sure that in the coming years the number of applications with HEC-RTS will increase.

Application to ecotourism – case study with Boi River trail

Despite not being a common application, hydrological forecasting can be used for developing warning systems that aim to assist in the management of ecotourism activities that are carried out close to watercourses. Among the most commonly performed ecotourism activities, trails can be highlighted. In many cases with trails, it is necessary to cross the river bed to complete the path proposed by the walk. Then, a hydrological forecasting system helps to predict how the flow conditions of these watercourses will be. If water levels and velocities are considered high, it is possible to determine the closing of the trail on that day to garantee the safety of tourists and avoid accidents.

This section presents one case study of a hydrological forecasting system that was developed to manage an ecotourism activity. Here, the system developed for the Boi river trail is is based on the HEC-RTS software.

Boi river trail

The Boi river watershed is located along the borders between the states of Rio Grande do Sul (RS) and Santa Catarina (SC), more specifically in the municipalities of Cambará do Sul (RS) and Praia Grande (SC). This watershed has an area of 112.87 km² and its main watercourses are the Perdizes stream, the Água Comprida stream, the Perdizes river, and the Boi river (Figure 4).

Because of an area presenting a unique landscape as well as a great diversity of fauna and flora, two Integral Protection Conservation Units were established in this location, namely, the Aparados da Serra National Park (PNAS) and the Serra Geral National Park (PNSG). These protected areas are widely known for their canyons, which are the largest in Latin America.

The topography of this watershed is characterized by an abrupt variation between the Campos de Cima da Serra plateau and the Coastal Plain. More specifically, the part of the watershed inserted onto the plateau, which belongs to RS, has a smooth to wavy relief with altitudes varying between 900 and 1200 meters. The valleys and steep hillslope formations, with altitudes between 100 and 1000 meters, belong to SC.

This big difference in relief directly influences the climate of the region, especially the annual rainfall and the mean annual temperature. In general, the RS part of the watershed has lower temperatures throughout the year (average of 15 ºC), and the highest rainfall (between 1700 and 2000 mm/year). The SC part of the watershed has average annual temperatures ranging between 18 and 20 ºC with rainfall of 1300 to 1500 mm/year (MMA, 2004). According to the Köppen climate classification, the climates of Praia Grande and of Cambará do Sul are Cfa and Cfb, respectively.

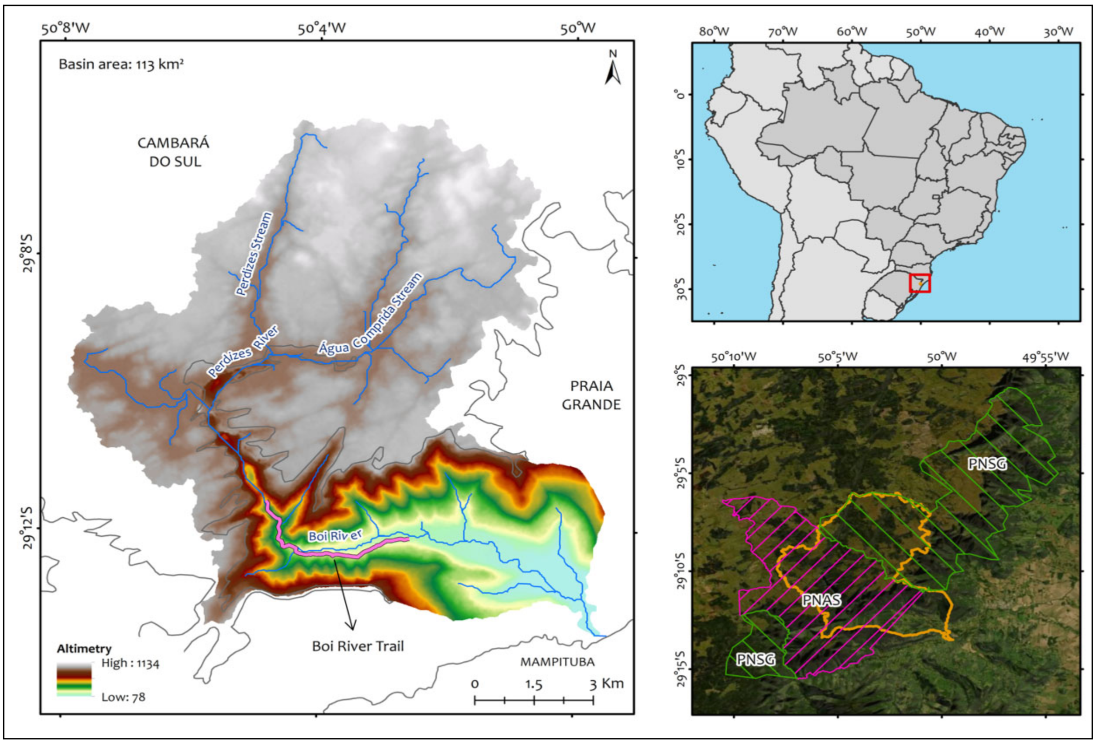
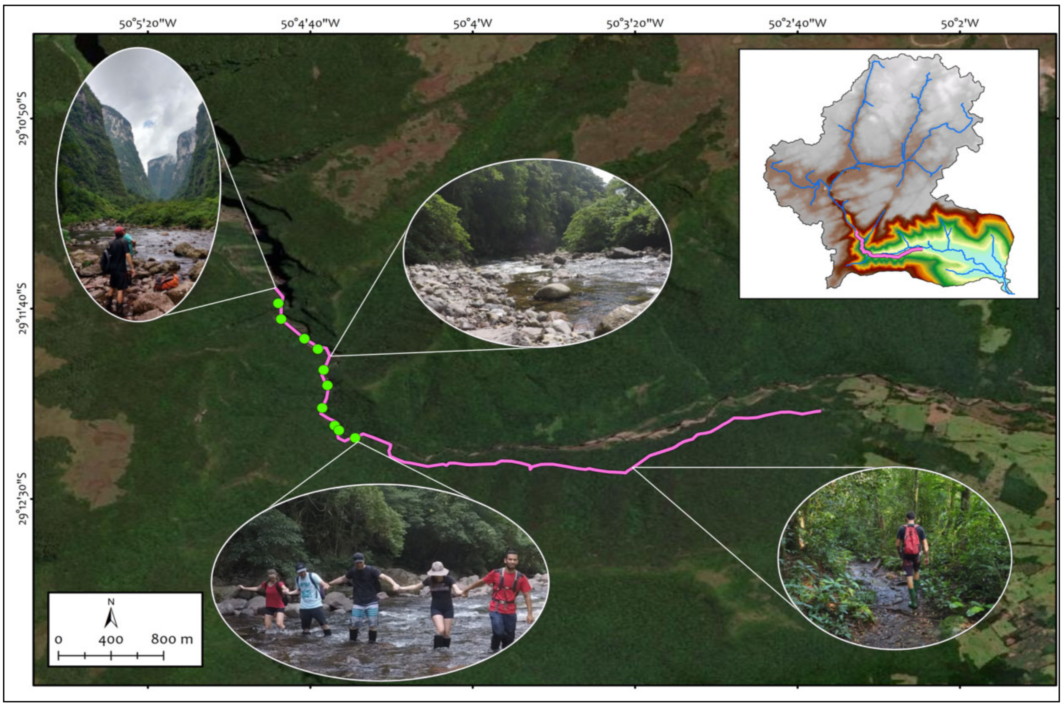


Figure 4. The Boi river watershed.

Every year, several people visit this region seeking to execute leisure and adventure activities in natural environments. Then, this place can be considered one of the most popular tourist spots in southern Brazil. Among the various existing tours, the Boi river trail stands out, which is carried out in the lower part of the Itaimbezinho canyon and is considered a trail with a high degree of difficulty in its execution (MAZZALI et al., 2021). The walk starts in the middle of the native forest (Atlantic Forest), but most of the path is made following the Boi riverbed, which automatically requires to cross it at some sections. For this reason, it is not always possible to carry out the trail, because depending on the water-flow conditions, mainly in terms of velocity and depth, people may not be able to cross the river. Figure 5 shows the path taken along the trail, the river crossing points, and some pictures of the place.



Source: ESRI Basemap (2022).

Figure 5. Overview of Boi river trail. The pink line shows the path taken during the Boi river trail and the green dots show the places where the riverbed is crossed during the walk.

To garantee the life secutiry of tourists who take this walk, the PNAS has adopted a criterion for closing the trail that is based on the water level of the Boi river and the Perdizes river which is its main tributary. Therefore, every day at 7 am, the PNAS rangers check the water level pointed on the linimetric rulers that are installed on these watercourses and, if the values are above a determined threshold, the trail is closed for visitation on that day.

However, when using this criterion, rainfall which is the main variable that can affect the variation of the velocity and depth of the Boi river is not considered.

In this way, when the water level of the Perdizes river and the Boi river are lower than the threshold ones established as the maximum for opening the trail, tourists will be able to participate in tours, even if it is raining in headwater regions. This critical situation can lead to the occurrence of emergency situations. For example, at the end of January 2021, six people were stranded at the middle of the path of the Boi river trail and had to stay overthere one night waiting for rescue. Fortunately, no one was injured at that occurrence (GLOBO, 2021).

In this context, one of the ways to improve the trail closure criterion would be through the insertion of rainfall data which are both observed and predicted, to try to predict how the Boi river level will change during the day. This can be done with the development of an operational hydrological forecasting system that can be easily applied by park managers.

Hydrological forecast system of the Boi river trail

From these considerations, a hydrological forecasting system was developed for the Boi river trail based on the HEC-RTS software version 3.2.1. For the application of this system, three other software developed by USACE were used together with the HEC-RTS, namely: i) MFP; ii) the HEC-HMS version 4.6.1 (USACE-HEC, 2016a); and iii) HEC-RAS version 5.0.7 (USACE-HEC, 2016b). A forecasting system scheme is shown in Figure 6.

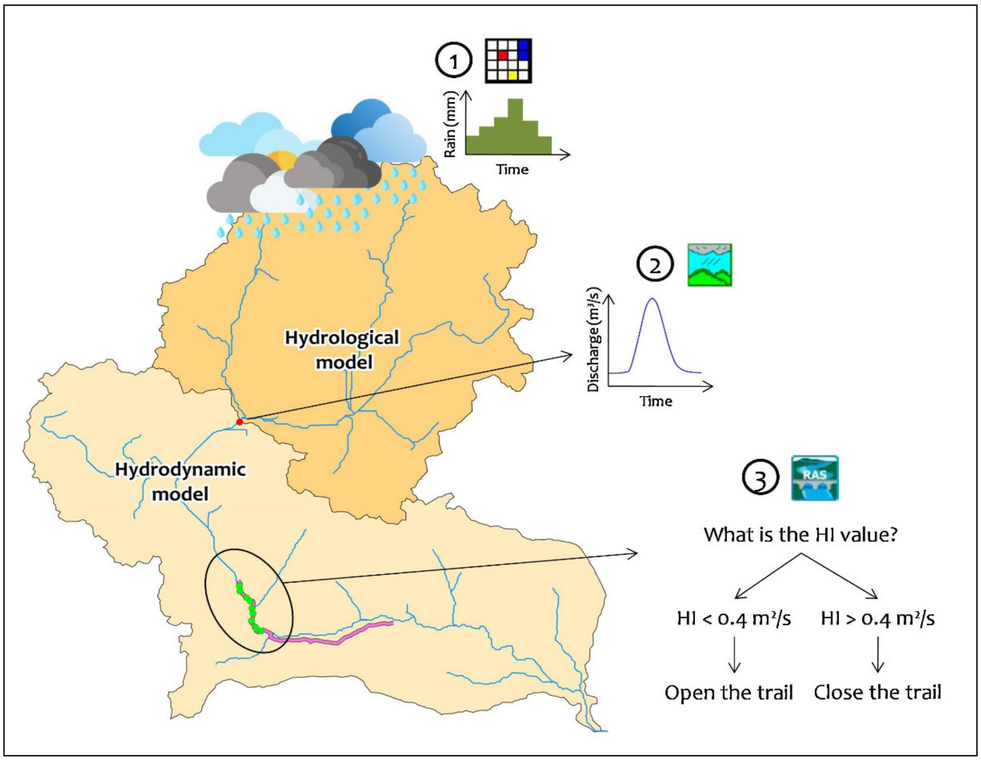


Figure 6. Boi river trail forecasting system. Note that HI means the hazard index.

The first step to carry out a forecast in the proposed system is the insertion of forecasted rainfall estimates in the MFP, which is the software responsible for manipulating the precipitation data. In this software, only the conversion of rainfall data is carried out to transform them into a format accepted by another software of the HEC family.

After entering the rainfall estimates into the MFP, these data are then used as input to the hydrological model in the HEC-HMS. In this case study, the HEC-HMS was applied to transform the forecasted rainfall data into the discharge for the area referring to the Perdizes river sub-watershed, i.e., they present the discharge that passes through the outlet of the Perdizes river sub-watershed, which is represented by the red dot in Figure 6.

The hydrographs obtained with the HEC-HMS application, referring to the outlet of the Perdizes river sub-watershed, are then inserted as input data in the hydrodynamic model HEC-RAS. This is done to propagate them to downstream points of interest, which are the points where tourists cross the riverbed during the trail. The flow propagation in HEC-RAS allows to obtain the arrival time of the flood wave at the places of interest, and also provides data regarding the velocity and depth of the flow at any desired point.

As the water-flow velocity and depth are considered by many authors as the variables that are most-strongly related to the loss of human stability when exposed to a water flow, the present study adopted the hazard index (HI) defined by Stephenson (2002) to determine the trail closures. The *HI* value can be obtained as the result of the product of velocity and depth of flow:

$$HI = h \cdot v \tag{1}$$

where is the depth (m); and is the velocity (m/s).

In this way, the trail is considered closed by the forecast system when the *HI* value exceeds 0.4 m^2/s at any point where tourists cross along the Boi river, represented by the green dots in Figure 6. This threshold adopted for the *HI* value is considered safe for children and conservative for adults and is used by the Australian Rainfall Runoff Guidelines (ARR) in its applications (COX et al., 2010). It is important to highlight that the *HI* values are evaluated by the system only for the opening hours of the trail, i.e., for the period from 7 am (the time when the rangers check the level of the Boi river in the morning) to 6 pm (the time when the trail is closed, considering a safety margin of 1 h in its opening hours).

In this case study, in order to test the applicability and efficiency of the system in correctly predicting the days when the Boi river trail should be closed, historical estimates of predicted rainfall from the Global Ensemble Forecast System v12

(GEFS) of NOAA (2020) were used. Thus, the predictions made to verify the effectiveness of the forecasting system were carried out for a past period. This allowed comparing the results relating to the determination of the opening or closing of the trail by the system with the observed data.

Regarding the GEFS rainfall estimates, it is worth noting that this is a database of ensemble rainfall estimates, i.e., it does not have only one forecast of the amount of rainfall that will occur in the future, but several different forecasts, as shown in the example in Figure 7. Each of the lines presented by the graph in Figure 7 represents a different forecast, i.e., a different ensemble member. All of them were obtained from the same meteorological model, but considering slight disturbances in the initial conditions of the meteorological model in order to consider the possible scenarios of the event's occurrence.

Therefore, the application of these estimates in the proposed forecasting system will result in not only one answer regarding the opening of the trail, but also in several answers. When analyzing the forecasted rainfall estimates presented in Figure 7, it is noted that there is a great difference among the rainfall depths of all the forecasts. This likely results in a different indication regarding the opening or closing of the trail. Thereby, instead of the system answering only "Open" or "Close" the trail, it is possible to obtain a probability related to the opening and closing for a given day.

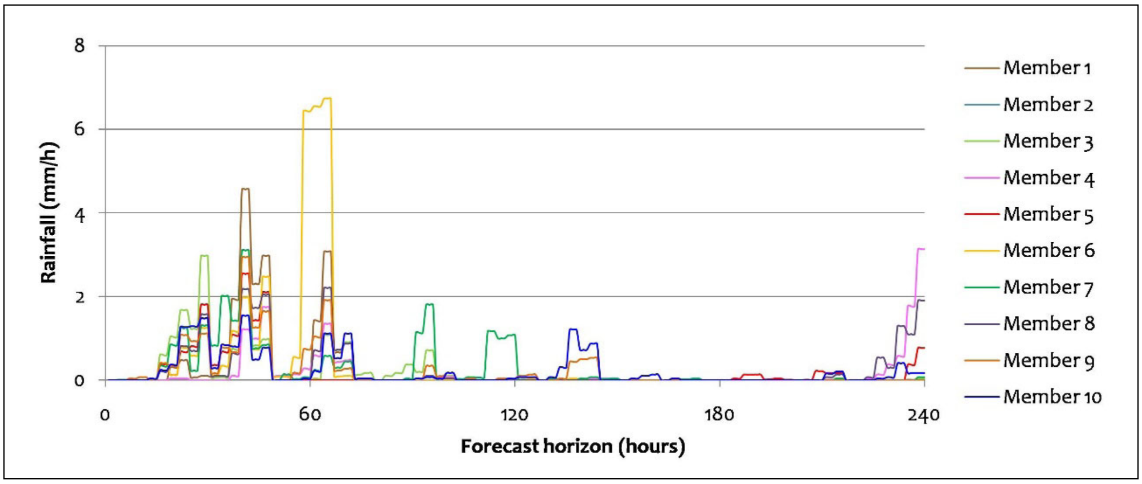


Figure 7. Example of GEFS predicted rainfall forecast for a day that has 10 future forecasts (members) in the ensemble.

To evaluate the performance of this forecasting system, the statistical metric of the ROC (Relative Operative Characteristic) diagram was applied. This method is commonly used for evaluating the occurrence of discrete events in systems that are based on ensemble prediction data, and provides as result the system's success rates and false alarm rates, which can be presented graphically. More details about this metric can be seen in Fan et al. (2016).

Figure 8 shows the results obtained by the forecasts using the ROC diagram. In this case, the results are also compared with the climatology performance equation. Forecasts generating points above this line can be considered good, i.e., they are more accurate in detecting events than issuing false alarms represented by the y-axis (POD – Probability of Detection), and a lower rate of false alarms, represented by the x-axis (POFD – Probability of False Detection). If the forecasts generate points below this line, the number of errors is greater than the number of hits, consequently, they are considered inefficient.

In this context, it is recognized that the shorter the forecast horizon, the better were the obtained results, having a higher success rate. The performance analysis demonstrated that the forecast system developed in this study presented satisfactory results concerning the decision of the opening and closing of the trail for up to 3 days in advance. For longer lead times, the larger uncertainties in the estimates reduced the correct detection of events and significantly increased the false alarm rate.

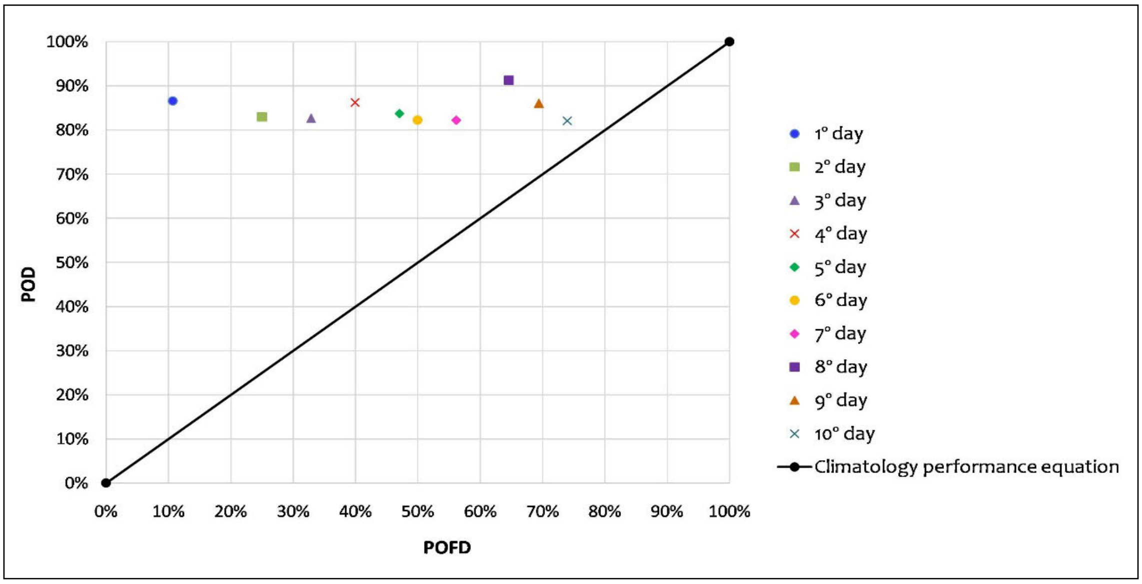


Figure 8. System performance analysis considering the statistical metric of the ROC diagram. In this case, the Probability of Detection (POD) and the Probability of False Detection (POFD) are presented considering all ensemble members.

The results related to the success rates and false alarm rates of the forecast system are presented in Table 2. Although the true alarm rate does not drop significantly with the increase in the forecast horizon, the false alarm rate increases considerably. Since the false alarm rate was always higher than 40%, we do not recommend to adopt horizons longer than four days in this system at this moment.

Based on the results above-mentiones, it can be said that the forecast system based on the HEC-RTS is a good tool for decision making on the opening and closing of the Boi river trail. This system can be used in conjunction with the current methodology where the PNAS rangers verify the water level of the linimetric ruler every day.

As the Boi river watershed is small and responds very quickly to rainfall events, it is clearely observed that the quality of discharge forecasts is closely linked to forecasted rainfall estimates. Despite this, the GEFS estimates performed well when applied to this study area as well as the forecasting system as a whole.

Furthermore, the developed system has the advantage of having a probability associated with the opening and closing of the trail. Such probabilities can be disclosed on the parks' communication platforms to assist in tourist planning and the trail visitation management.

Table 2. True alarm rates and false alarm rates of the proposed forecasting system.

Forecast horizon	True alarm rate	False alarm rate
1º day	86.8%	10.7%
2º day	82.9%	25.0%
3º day	82.7%	32.8%
4º day	86.2%	40.0%
5º day	83.7%	47.0%
6º day	82.3%	50.0%
7º day	82.3%	56.2%
8º day	91.2%	64.6%
9º day	86.1%	69.4%
10º day	82.0%	74.0%

Final remarks

The practice of activities in environmentally-preserved places has grown in the last decades. The growth of ecotourism brings new issues about hydrological risks in Brazil. Although interactions between nature and human beings can generate many benefits, tourists can be intensively exposed to natural hazards in environmentally-preserved places. Therefore, in a risk management which is essential to minimize negative impacts due to this proximity, we presented hydrological forecasting as one technique for supporting early warning systems in environmentally-preserved places.

Hydrological forecasting has been applied in various sectors, including in flood risk management. However, its application in hydrological risk management related to ecotourism is not well explored. Therefore, concerning ecotourism as a potential source of income, it is essential to ensure the tourists aiming to avoid the occurrence of material or human damages.

Technological advances should contribute to improving rainfall estimates, as well as reducing the computational time for data processing. This contributes to hydrological forecasting development to provide results with more reliability and, consequently, reduce false warnings. Hence, hydrological forecasting can be helpful for warning systems related to ecotourism practices. However, the development of hydrological forecasting should take into account the simple and practical interpretation of the results by the managers and decision-makers. Besides, in a complementary way, an early warning system for ecotourism should include training the tourist guides and defining direct and clear communication with the tourists and local community.

References

BARTHOLMES, J.; TODINI, E. Coupling meteorological and hydrological models for flood forecasting. **Hydrology and Earth System Sciences**, v. 9, p. 333-346, 2005.

BORSCH, S.; KHRISTOFOROV, A.; KROVOTYNZEV, V.; LEONTIEVA, E.; SIMONOV, Y.; DERIUGINA, V. Hydrologic forecasts verification and comparison of forecasting methods. **Preprints**, 2018080507, 2018. DOI: 10.20944/preprints201808.0507.v1.

BURKARD, S.; FUCHS-KITTOWSKI, F.; MÜLLER, R.; PFÜTZNER, B. Crowd sourcing and mobile sensing for flood management in small catchment areas. **CEUR Workshop Proceedings**, v. 2197, p. 110-127, 2018.

CEPED/UFSC. Centro Universitário de Estudos e Pesquisas sobre desastres / Universidade Federal de Santa Catarina. **Atlas Brasileiro de Desastres Naturais: 1991 a 2012. Volume Brasil. 2ª Edição: revisada e ampliada.** Florianópolis: CEPED/UFSC, 2013. Available on: <https://s2id.mi.gov.br/paginas/atlas/>. Accessed February 20th, 2022.

CHARLEY W.J. HEC-RTS (real-time simulation) version 2 for real time flood forecasting and water control. In: **Proceedings of 2nd Joint Federal Interagency Conference**, Las Vegas, 2010.

COLLISCHONN, W.; TUCCI, C.E.M. Previsão sazonal de vazão na bacia do rio Uruguai 1: ajuste e verificação do modelo hidrológico distribuído. **Revista Brasileira de Recursos Hídricos**, v. 10, p. 43-59, 2005.

COX, R.J.; SHAND, T.D.; BLACKA, M.J. Australian Rainfall and Runoff revision Project 10: appropriate safety criteria for people. **Water Research,** v. 978, 31p, 2010.

CPRM – Serviço Geológico do Brasil. **SACE – Sistema de Alerta de Eventos Críticos.** 2022. Avaiable on: <https://www.cprm.gov.br/sace/>. Accessed: January 10th, 2022.

EM-DAT. The Emergency Disasters Database. **Brazil.** Available on: <https://

public.emdat.be/data>. Accessed February 21th, 2022.

FAN, F.M. **Previsão por conjunto de vazões afluentes a reservatórios em grandes bacias hidrográficas brasileiras.** Tese (Doutorado em Recursos Hídricos e Saneamento Ambiental), Instituto de Pesquisas Hidráulicas da Universidade Federal do Rio Grande do Sul. Porto Alegre. 2015. 424p.

FAN, F.M.; PONTES, P.R.M.; COLLISCHONN, W.; BUARQUE, D.C. Sobre o uso da persistência de previsões determinísticas de vazão para a tomada de decisão. **Revista Brasileira de Meteorologia**, v. 31, p. 218-228, 2016.

FAN, F.M.; RAMOS, M.H.; COLLISCHONN, W. Sobre o uso de previsões hidrológicas probabilísticas para tomada de decisão. **Revista Brasileira de Recursos Hídricos**, v. 20, n. 4, p. 914-926, 2015.

FREUDENTHALER, B.; STUMPTNER, R. Adaptive flood forecasting for small catchment areas. In: **International Conference on Computer Aided Systems Theory.** Springer, Cham. 2015. p. 211-218.

GABORIT, E.; ANCTIL, F.; FORTIN, V.; PELLETIER, G. Hydrologic evaluation of spatially disaggregated global ensemble rainfall forecasts. **Hydrological Processes**, v. 28, p. 4682-4693, 2014.

GLOBO. **Em resgate de 21 horas, seis pessoas ilhadas são retiradas de uma trilha após rios encherem com chuva em SC.** 2021. Avaiable on: <https://g1.globo.com/sc/santa-catarina/noticia/2021/01/29/em-resgate-de-21-horas-seis-pessoas-ilhadas-sao-retiradas-de-trilha-apos-rios-encherem-com-chuva-em-sc-video.ghtml>. Accessed: February 20th, 2021.

ICMBIO. Instituto Chico Mendes de Conservação da Biodiversidade. **Monitoramento da Visitação em Unidades de Conservação Federais: Resultados de 2019 e Breve Panorama Histórico**. Brasília: Ministério do Meio Ambiente, 2020. 20p.

MARTÍNEZ-GOMARIZ, E.; GÓMEZ, M.; RUSSO, B. Experimental study of the stability of pedestrians exposed to urban pluvial flooding. **Natural Hazards**, v. 82, p. 1259-1278, 2016.

MAZZALI, L.H.; DIAZ, L.R.; KOBIYAMA, M.; CAMPAGNOLO, K. Análise dos Trechos da Trilha do Rio do Boi no Parque Nacional de Aparados da Serra. **Biodiversidade Brasileira**, v.11, p.134-147, 2021.

MELLER, A. **Previsão de cheias por conjunto em curto prazo.** Tese (Doutorado em Recursos Hídricos e Saneamento Ambiental), Instituto de Pesquisas Hidráulicas da Universidade Federal do Rio Grande do Sul. Porto Alegre. 2012. 204p.

MMA – MINISTÉRIO DO MEIO AMBIENTE. **Plano de manejo do Parque Nacional de Aparados da Serra e Serra Geral. Encarte 1 – Contextualização da UC.** Brasília: Ministério do Meio Ambiente, 2004. 54p.

MONTEIRO, L.R.; KOBIYAMA, M.; ZAMBRANO, F.C. Mapeamento de Perigo de Inundação. Porto Alegre: UFRGS/IPH/GPDEN, 2015. 91p. (Trabalho Técnico GPDEN No. 3). Available on: <https://www.ufrgs.br/gpden/wordpress/wp-content/uploads/2015/12/inundacao.pdf>.

MONTEIRO, L.R.; SANTOS, C.I.; KOBIYAMA, M.; CORSEUIL, C.W.; CHAFFE, C.L.B. Effects of return periods on flood hazard mapping: an analysis of the UFSC Campus Basin, Florianópolis city, Brazil. **Brazilian Journal of Water Resource**s, v.26, Epub, 2021.

NOAA - NATIONAL OCEANIC AND ATMOSPHERIC ADMINITRATION. **Global Ensemble Forecast System (GEFS).** Avaiable on: <https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-ensemble-forecast-system-gefs>. [Accessed: February 5th, 2020].

SENE, K. **Hydrological Forecasting**. In: Hydrometeorology. Springer, Dordrecht. 2010. Available on: <https://doi.org/10.1007/978-90-481-3403-8_4>.

SILVEIRA, G.L.; TUCCI, C.E.M.; SILVEIRA, A.L.L. Quantificação de vazão em pequenas bacias sem dados. **Revista Brasileira de Recursos Hídricos**, v. 3, p. 111-131, 1998.

SIQUEIRA, V.A.; COLLISCHONN, W.; FAN, F.M.; CHOU, S.C. Ensemble flood forecasting based on operational forecasts of the regional Eta EPS in the Taquari-Antas basin. **Revista Brasileira de Recursos Hídricos**, v. 21, p. 587-602, 2016.

STEPHENSON, D. Integrated flood plain management strategy for the Vaal. **Urban Water**, v.4, p. 425-430, 2002.

TUCCI, C.E.M. **Modelos Hidrológicos.** Porto Alegre: Universidade Federal do Rio Grande do Sul, 1998. 669 p.

TUCCI, C.E.M.; COLLISCHONN, W. Previsão de vazão. In: TUCCI, C.E.M; BRAGA, B. (eds.) **Clima e Recursos Hídricos no Brasil**. Porto Alegre: ABRH, 2003. p.281-348.

UNDRR – UNITED NATIONS FOR DISASTER RISK REDUCTION. **Terminology on Disaster Risk Reduction UNDRR**. Geneva: Cornell University Press, 2009.

UNDRR – UNITED NATIONS FOR DISASTER RISK REDUCTION. **Sendai Framework for Disaster Risk Reduction 2015-2030** [online]. 2015. Available on: <https://www.preventionweb.net/publications/view/43291>. Accessed February 28th, 2020.

UNDRR; CRED. – UNITED NATIONS FOR DISASTER RISK REDUCTION; CENTRE FOR RESEARCH ON THE EPIDEMIOLOGY OF DISASTER. **Human Cost of Disasters**: **An overview of the last 20 years 2000-2019.** Geneva: [s. n.], 2020. Available on: <https://doi.org/10.18356/79b92774-en>.

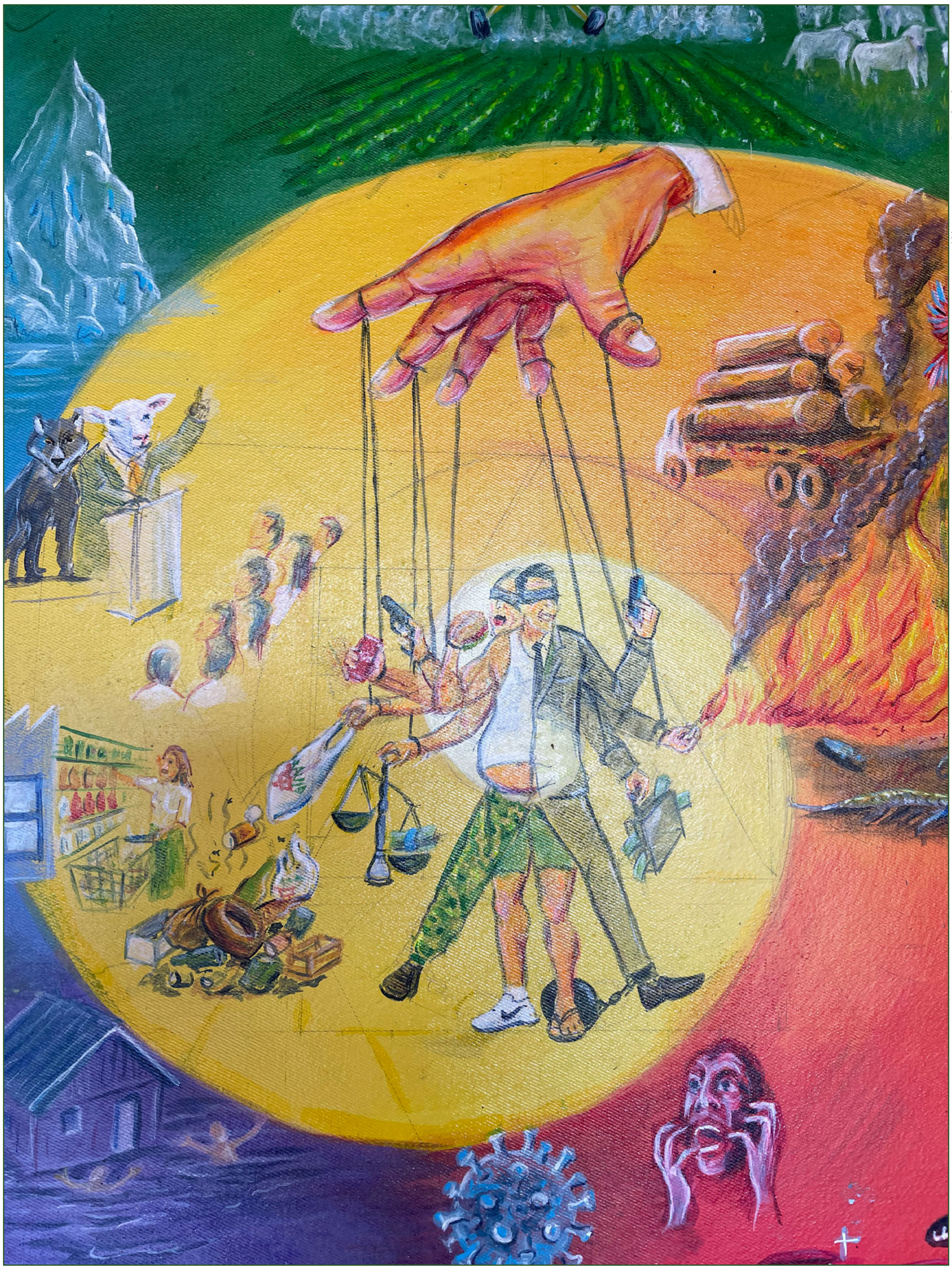
USACE-HEC. **Hydrologic Modeling System, HEC-HMS v4.2.1 – User's Manual.** US Army Corps of Engineers, Hydrologic Engineering Center. 2016a. 614 p.

USACE-HEC. **River Analysis System, HEC-RAS v5.0 – User's Manual.** US Army Corps of Engineers, Hydrologic Engineering Center. 2016b. 960 p.

USACE-HEC. **Real Time Simulation, HEC-RTS v. 3.1.1 – User's Manual.** US Army Corps of Engineers, Hydrologic Engineering Center, 2020. 528 p.

WANDERS, N.; THOBER, S.; KUMAR, R.; PAN, M.; SHEFFIELD, J.; SAMANIEGO, L.; WOOD, E.F. Development and evaluation of a pan-European multimodel seasonal hydrological forecasting system. **Journal of Hydrometeorology**, v. 20, n. 1, p. 99-115, 2019.

YASSEN, Z.M.; JAAFAR, O.; DEO, R.C.; KISI, O.; ADAMOWSKI, J.; QUILT, J.; EL-SHAFIE, A. Stream-flow forecasting using extreme learning machines: a case study in a semi-arid region in Iraq. **Journal of Hydrology**, v. 542, p. 603-614, 2016.



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