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Experimental and representative basins in Brazil: A review

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INTRODUCTION

Hydrometeorological monitoring is an essential tool for supporting an integrated and sustainable water resources management. Monitoring provides the necessary data to evaluate trends in water quality, quantity and distribution; to run hydrological models and to advance our understanding of hydrological processes (VILLAS-BOAS; OLIVERA; DE AZEVEDO, 2017; WANG; FU, 2018). Field hydrology activities at basin scale usually take place in experimental and representative basins (ERB). Experimental river basins are usually defined as drainage areas in which well-known information regarding land cover, soil type, and hydrological characteristics can be obtained (TOEBES; OURYVAEV, 1970; WHITEHEAD; ROBINSON, 1993). Representative basins are well-instrumented basins whose purpose is to serve as a surrogate for testing hydrological processes forced by a set of representative data (LINSLEY, 1976).

Literature reviews related to monitoring of water quality or quantity were done on a national scale in many countries worldwide (e.g., BURT; MCDONNELL, 2015; HARRIGAN et al., 2018; JIANQING et al., 2016). Additionally, surveys addressing the physical, chemical, and biological aspects of water were carried out in Slovenia (ŠRAJ et al., 2008), England and Wales (COLLINS et al., 2012), China (JIANQING et al., 2016), Chile (VALDÉS-PINEDA et al., 2014), and the USA through the US Department of Agriculture-Agricultural Research Service's (USDA-ARS) Experimental Watershed Network (ZIEMER; RYAN, 2000).

In Brazil, the first substantial effort related to the monitoring of small basins initiated in the early 1970s as a result of a bilateral cooperation between the Superintendence for Development of the Northeast (SUDENE, in Portuguese) and the former ORSTOM (French Overseas Department of Scientific Research and Technology) (CADIER, 1996). Since 2001, a remarkable integrated

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monitoring of ERB in Brazil has been carried out by the Brazilian Hydrology Network for the Semi-arid Region (REHISA). REHISA is composed of eight federal universities from the north-eastern region (UFPB, UFRN, UFCG, UFAL, UFPE, UFRPE, UFC, and UFCG) and one state agency (FUNCEME).

Monitoring data from ERB have been used for a number of purposes in Brazil, including the calibration and validation of models (RODRIGUEZ; TOMASELLA, 2016; VILLAS-BOAS; OLIVERA; DE AZEVEDO, 2017; ZEMA et al., 2018); increasing crop productivity (ALMEIDA et al., 2007), tracing sediment sources in rural areas (TIECHER et al., 2017), and quantifying the infiltration and recharge of aquifers (COELHO et al., 2017; SALLES et al., 2018).

Given the relevance of field hydrology studies, this study seeks present a review of the ERB monitored in Brazil and answer key questions regarding the location of the monitoring sites, period of monitoring and lessons learned. Ultimately, this review intends to identify which advances have been achieved in hydrological science? To this end, we describe the geographic locations, characteristics of monitoring activities, and main findings in these basins.

MATERIAL AND METHODS

Terminology, Data Collection and Analysis

In this study, the term "hydrologic monitoring" refers to the monitoring of at least rainfall (P) or streamflow (Q) in association with other types of monitoring related to hydrology (water quality, soil moisture, etc.) when available. To support the analysis, we considered the following hydrographic regions: Amazon (AMZ), East Atlantic (ALT), Western Northeast Atlantic (AOC), Eastern Northeast Atlantic (AOR), Paraná (PRN), Parnaíba (PNB), Paraguay (PRG), São Francisco (SFO), South Atlantic (ASU), Southeast Atlantic (ASD), Tocantins-Araguaia (TOC), and Uruguay (URU).

The information about the Brazilian ERB published in scientific literature (e.g., peer review journals, dissertations, books) were compiled using Google Scholar, Web of Science, Scopus, and SciELO databases. The categories used to organize the collected information include geographical coordinates, drainage area, hydrological variables monitored, time features (e.g., monitoring time resolution), monitoring devices/sensors, main findings, and published results.

Descriptive statistics and thematic maps were used to produce temporal and spatial information relative to each ERB, according to the categories listed above. Fifteen research topics from the main top-ranked journals in water resources, according to Journal Citation Reports (or JCR, a product of Web of Science Group), were selected to identify the main research lines established in the EBRs in Brazil. The number of publications produced using data from these basins are presented herein, and the relationship of the publications with the monitoring characteristics of each unit is explored based on scores.

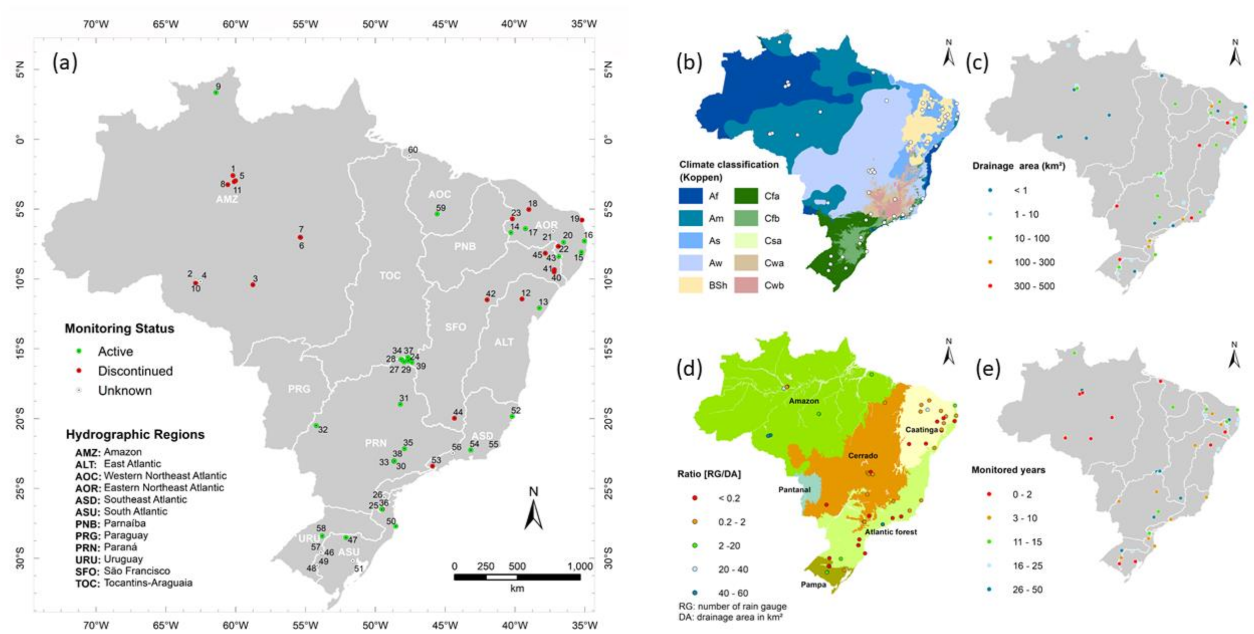
RESULTS AND DISCUSSION

General information

A total of 60 ERB were identified in Brazil: 28 active, 20 discontinued, and 12 with unknown monitoring status (Figure 1). A detailed information on each individual ERB can be found in (MELO et al., 2020). Most of the discontinued ERB are in the AMZ. Most of these Amazonian ERB were monitored for up to three years, with only one exception (ID-3), whose monitoring period ranged from 1977 to 1983. The PRN region contains most of the active ERB (13), representing 26% of the total amount in Brazil.

The main land use in the ERB is natural forest in pristine condition (40%), followed by agriculture (20%), and pasture (17%). Approximately 23% of ERB occur in urban areas or areas predominantly reforested (e.g., eucalyptus). Monitored sites were not identified in the Paraguay, Tocantins-Araguaia, and Parnaíba units. The AOR region has five active ERB and four deactivated sites. Together with two sites in the SFO hydrographic region, the four deactivated sites in the AOR region (ID-18, 19, 22, and 23) compose half of the representative basins installed by SUDENE/ORSTOM in the 1960s and 70s. In total, 10 ERB were set up, each one containing a number of small sub-basins (≥ 0.01 km²), totaling 43 monitored sites (CADIER, 1994).

Figure 1 –(a) Location of the ERB across Brazilian hydrographic regions; (b) climate classification across sites; (c) drainage area of monitored basins; (d) biomes across sites; (e) monitored years of monitores basins .



Hydrological variables monitored and research lines

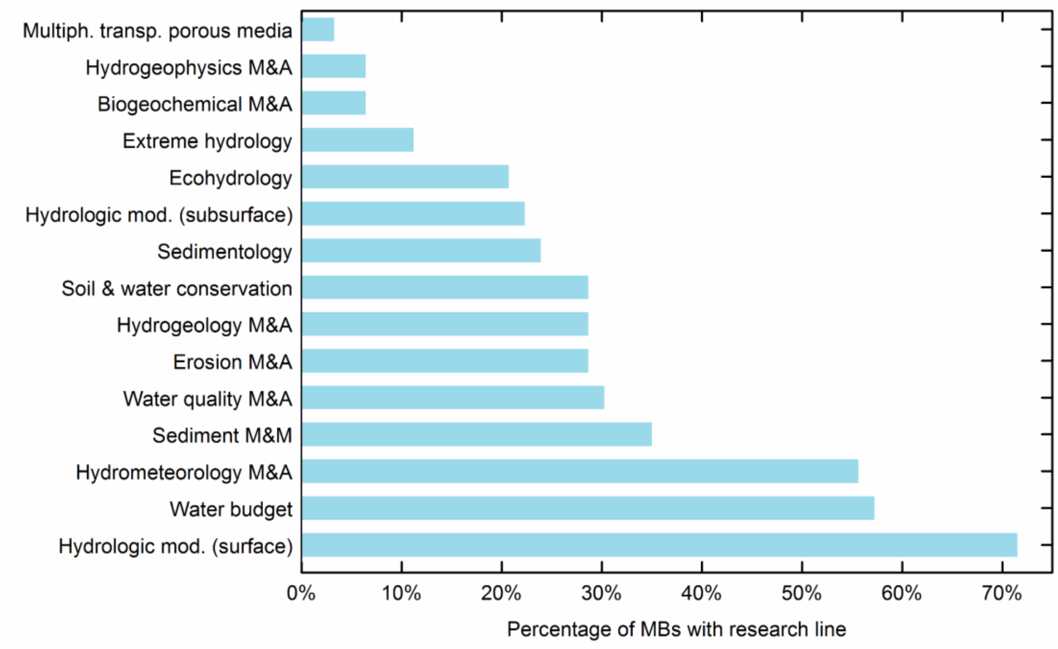
A wide variety of hydrological variables are (were) monitored in the ERB, including P, Q, soil moisture (SM), groundwater level (GW), sediment yield (SY), evapotranspiration (ET) and surface water quality (WQ). The most comprehensive assessment of the hydrological process is provided by the Capetinga (ID-29, PRN hydrographic region), where seven hydrological variables are monitored: P, Q, soil moisture (SM), groundwater level (GW), sediment yield (SE), evapotranspiration (ET), and surface water quality (WQ).

The most frequently monitored variables in Brazilian EBRs are P and Q; only four ERB do not monitor both. Almost 40% of ERB monitor (or have monitored) only three variables; ET or GW is frequently the third variable in addition to P and Q. ET is measured or estimated in 32 ERB, ~53% of the Brazilian total, which is a relatively low number, considering that ET is a major output of the water budget (VINUKOLLU et al., 2011).

We identified 24 ERB (40%) that kept a continuous record of WQ data in Brazil. Around 30% of ERB develop or carry out isolated campaigns in "water quality monitoring and assessment" research in Brazil (Fig. 3). These numbers are worrisome, considering the relatively short outreach of the Brazilian sanitation system. Moreover, the lack of water quality monitoring limit a proper understanding of temperature, organic pollution, variability of nutrient concentrations, and impact of land use change (TUNDIS VITAL; DE PAULA LIMA; DE CAMARGO, 1999; WHITEHEAD; ROBINSON, 1993). Sediment yield measurements have been carried out in 17 ERB, in contrast to the 71 runoff plot-scale surveys in Brazil (ANACHE et al., 2017), 1819 catchments registered in the US Geological Service (USGS 2018).

The three main research lines, identified in more than ~50% of the ERB, are: "surface hydrologic modelling," "hydrometeorology monitoring and assessment (M&A)," and "water budget" (Figure 2). Conversely, "multiphase transport phenomena in porous media," "biogeochemical M&A," "hydrogeophysics M&A," and "extreme hydrology," are topics studied in less than 20% of the EBRs. It is worrisome that some of those topics are poorly studied in the Brazilian EBR. Existing bias towards some research topics and neglect of others reveal an urgent need for new field experimentation in Brazil. For example, we did not identify a single basin where the research line "environmental fluid dynamics" was developed. In times when science is becoming more and more interdisciplinary, it is reasonable to reflect as to whether focusing only on traditional topics in hydrology (e.g., water budget, hydrologic modelling, etc) will effectively contribute to the advancement of our knowledge in this discipline.

Figure 2 – Frequency of research topics within Brazilian EBR's during the period from 1970 until 2018. The symbols "M&A" and "M&M" mean "monitoring and assessment" and "monitoring and modelling," respectively.



Hydrological variables monitored and research lines

Different instruments and methods have been used to monitor hydrological variables in the EBR (Table 1). Streamflow has been quantified using chemical tracers, stage gauges, acoustic doppler current, among others. Evapotranspiration is most commonly estimated indirectly using the Penman-Monteith equation, but in some cases, more accurate methods (e.g., lysimeter or eddy covariance) have been applied. The soil water content has been monitored by tensiometers, time/frequency domain reflectometry, neutron probes, and lysimeters.

The diversity of instruments and measurement techniques available in the EBR allows for the development of studies that contribute to a general comprehension of the water cycle and the discovery and comprehension of specific processes. For example, Almeida et al. (2007) analyzed the growth and water balance of the Eucalyptus grandis hybrid crop. They determined that eucalyptus trees use water from the top layers (the first 60 cm) of soil and that as the trees become older, water-use efficiency decreases significantly. Mello et al. (2018) highlighted that forest cover rates can be used as indicators of stream health in tropical agricultural basins after the land cover and land use have influenced the water quality (sediment, nutrients, and coliform loads) and quantity (infiltration and runoff rates).

Table 1 – Instruments and techniques used to monitor hydrological variables in the EBR.

Hydrological variable	Measuring device/method/parameters
Rainfall	Automatic and conventional gauges
Streamflow	Stage gauge, Acoustic Doppler Current (ADCP), Weir, Flume, Current Meter, Chemical Tracer
Evapotranspiration	Bowen, Penman-Monteith, Class A Pan, Eddy Covariance, Lysimeter, Meteorological Station
Groundwater level	Automatic and manual
Sediment	Fraction (suspended and bed loads), Organic matter
Water Quality	pH, temperature, turbidity, electric conductivity, specific condutance, alkalinity, color, dissolved oxygen, organic suspended solids, total organic fraction, total inorganic fraction, thermotolerant coliforms, nitrogen, phosphorus, Solutes, Biochemical Oxygen Demand, potassium, calcium, magnesium, grease and oil content, heavy metal pollution index.
Soil Moisture	Lysimeter, Neutron Probe, Time/Frequency Domain Reflectometry, Tensiometer

Monitoring spatial features

The drainage areas of the EBR range from 0.02 km2 (ID-3, ID-4, and ID-10) to 563 km2 (ID-58) (Figure 1). In total, 41 EBR identified in this study have drainage areas less than 20 km², representing 68% of the total. The large number of small basins is probably due to the need for better control of hydrological processes at this scale. The large number of small basins combined with the considerable quantity of available rain gauges provides a significant density for the ground-based precipitation monitoring network, resulting in most EBR having at least 0.2 gauges per km² (Figure 1). The EBR in Figure 1d with RG/DA ratios >10 have areas below 1 km². Field hydrology studies were not found in Pantanal, one of the six Brazilian biomes. Most of these EBR are located in the Amazon, Caatinga, and Atlantic forest biomes, each with ~15 EBR.

EBR have been used to assess rainfall spatial homogeneity over small areas. Barbosa et al. (2018) observed rainfall homogeneity at four rain gauges analyzed in the Guaraíra experimental basin (ID-16, AOR hydrographic region). Marques et al. (2017) detected a similar seasonal distribution of rainfall in an area of 2,065 km² in the Piabanha river basin (ID-54, ASD hydrographic region); however, differences from 100 mm to 1000 mm were found among three rain gauge measurements in the same year.

Monitoring temporal features

In general, P and Q are monitored with sub-hourly time resolution. Our review identified 353 rain gauges in the EBR with recording intervals ranging from sub-hourly to daily. From this total, ~82% of the EBR collect data automatically on different time scales, with 12% measuring on a daily scale (automatic or manual) and 13% without information about the data collection interval. Sub-hourly Q monitoring was carried out in ~40 EBR. Conversely, we identified only four basins in which Q was measured on weekly to monthly time intervals.

The time resolution of GW data also varies from sub-hourly to monthly scales; however, such information was not available for most of the basins, 40 in total. Seven EBR present weekly to monthly data, while nine provide sub-hourly information about the GW. A similar situation of unavailability of information is reported regarding WQ and SM monitoring.

If the lack of information regarding the sampling intervals of certain variables means a low frequency of field measurements, then it is correct to infer that most EBR in Brazil are underexploited, scientifically speaking. Time resolution has a significant impact on hydrological study results, especially when the hydrological variable is the primary input data for models (e.g., P) (BRUNEAU et al., 1995). Moreover, high-temporal monitoring may reveal unknown environmental impacts (NÓBREGA et al., 2018). Therefore, increasing the sampling interval might be a major need common to most ongoing field activities in Brazil.

The number of EBR in Brazil has increased in all hydrographic regions over the years. The most significant increase occurred from 2001 to 2015, especially in the PRN region. Consequently, almost 70% of the EBR have between (or were active during) 1 and 20 years of monitoring, with an average of ~12 years (Figure 1). Four EBR have ~30 years of monitoring, and three EBR have been monitored for more than 40 years (Figure 1). The increase in the number of EBR, which occurred from 2001 to 2010, is probably related to the availability of grants provided by Brazilian public research agencies during this time period. Likewise, the decrease in the number of EBR between 2011 and the present day is probably linked to the reduction of public funds for research purposes.

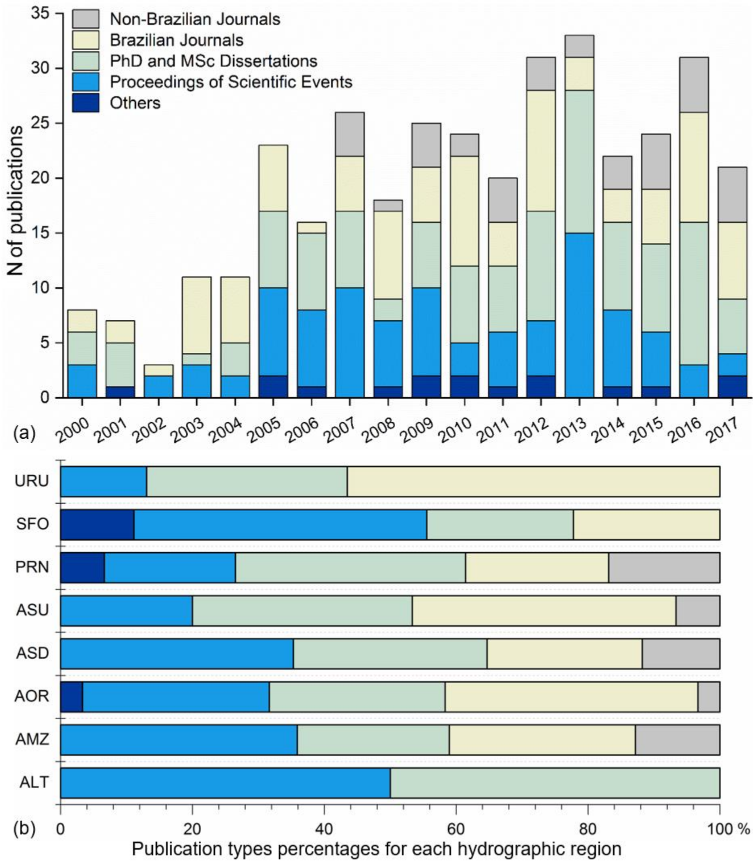
No active EBR was found in the ASU hydrographic region before 2000. In addition, there was a lack of monitoring sites in the ASD hydrographic region before 1986 and between 1996 and 2005. Basin monitoring programs in Brazil started in the early 1960s with the Juatama representative basin (ID-18) being the first of the various representative basins installed by SUDENE in the Brazilian semi-arid region. Monitoring activities occurred by means of campaigns rather than continuously over time. In contrast, Europe (IHP/HWRP 2010) started monitoring basins almost half a century earlier, in 1924. At the end of the 1990s, approximately 30 years later, Brazil had ~20 EBR, with most in the PRN and AMZ hydrographic regions. The total number of EBR reached its maximum value in the 2000s, when 34 new projects began in all hydrographic regions. The monitoring of the newest EBR (ID-50) started in 2015 in the ASU hydrographic region.

Publications and main findings

As part of an effort to promote advances in hydrology, several types of studies (e.g., research papers in non-Brazilian and Brazilian journals or proceedings of scientific conferences) have been completed (Figure 3). Most of the information, knowledge, and advances resulting from all the hydrologic monitoring in Brazil have not been widely shared with the international community, for example, less than 20% of publications related to Brazilian EBR have been published in non-Brazilian journals (Figure 3). Regardless of the fact that some papers published in Brazilian journals are in English, the amount of data published in scientific journals is modest (<50%).

Field-based studies in Brazil are part of graduate and undergraduate research programs; hence, it is expected that theses, dissertations, and conference papers will account for a not-so-modest fraction (~30%) of publications using monitoring data. However, our review indicates that these theses, dissertations, and conference papers (usually in Portuguese) do not become peer-reviewed literature for a broader audience. Although we do not intend to advocate in favor of the "publish-at-all-cost" philosophy that nourishes predatory journals, it is curious and worrisome that more than 50% of Brazilian publications present precious observation data that do not cross Brazilian borders.

Figure 3 – (a) Time-distribution of publication types; (b) publication types by hydrographic region (b); other publication types: institutional and governmental reports, websites, and interviews.



Recently, a study carried out by Clarivate Analytics for CAPES (Brazilian Coordination for the Improvement of Higher Education Personnel, acronym in Portuguese) revealed that Brazil is one of the largest producers of research publications globally, but in terms of citation impact, Brazilian research publications are below the world average (*https://jornal.usp.br/wp-content/uploads/2019/09/ClarivateReport_2013-2018.pdf*). This probably occurs because most studies address local interests published in journals of a limited regional audience or are restricted to theses and dissertations. Therefore, the graduate courses in Brazil should provide means for publishing papers in journals that reach a wider scientific community, including those related to hydrological studies. The same study performed by Clarivate Analytics also identified that papers of high impact in Brazil are usually associated with international research collaborations. Thus, papers from collaborative studies located in strategic regions of interest to the wider international hydrology community such as the Amazon probably have greater citation impact than studies from other regions of Brazil.

What has prevented the findings in those Brazilian EBR from being shared among a wider community? Is the degree of basin instrumentation or the duration of monitoring periods insufficient? Or perhaps the poor variety of monitored variables and the low number of gauges have limited the applicability of the results produced from such EBR. We do not intend to suggest that basins with low publication rates are less relevant than the others. Our understanding is that every effort to maintain an experimental site is commendable, provides valuable information, and has the potential to contribute to advances in hydrologic engineering. Our concern is that such contribution may not reach the wider community that deals with hydrology and water resources in general.

We identified five major topics addressed among the field studies in Brazil: runoff generation, sediment transport, spatio-temporal rainfall patterns, water quality, impacts of land use and land cover change (LUCC), and groundwater recharge. Climate change, in spite of being an important research issue, is not among the most popular topics addressed in the EBR. We identified only eight basins that provide data for climate change studies, most of them in the SFO hydrographic region and others in the AMZ, AOR, and PRN regions (e.g., MELO; WENDLAND, 2017; MONTENEGRO; RAGAB, 2010, 2012). There are also specific topics that are addressed in a few EBR, for example, recent studies using natural and radioactive tracers as tools to investigate and solve hydrological problems (FERREIRA et al., 2018a, 2018b).

Based on the perspective of 230 scientists from different continents, Blöschl et al. (2019) listed 23 unsolved problems in hydrology. Although field hydrology researches in Brazil will not likely solve all 23 problems, we were able to identify 55 EBR whose data may help answer 19 of them (Figure 4). The problem most addressed in Brazilian field experiments (42 EBR), and whose definitive answer may come in the near future is problem no. 4 (BLÖSCHL et al., 2019): "What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?"

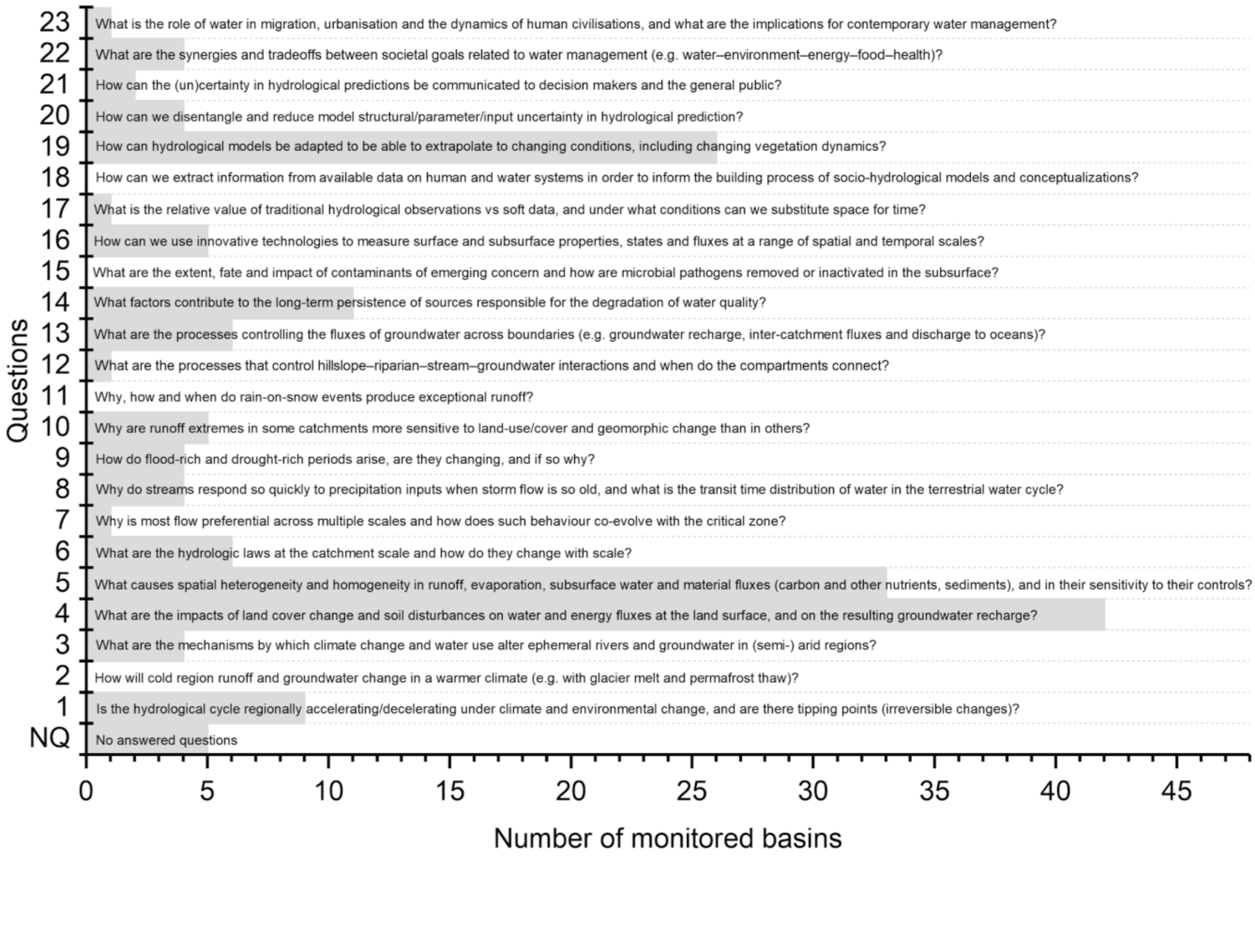
There are more than 25 EBR that may help solve problems related to "Space variability and Scaling" (no. 5) and "Modelling methods" (no. 19) (Figure 4). Given the types of Brazilian climates, we were unable to identify contributions to answer problems from Blöschl et al's. (2019) list related to runoff and groundwater change in cold regions (no. 2); and runoff produced by rain-on-snow (no. 11). Moreover, problem no. 15 (impacts of contaminants and removal of microbial pathogens in the subsurface) and no. 18 (use of data for building socio-hydrological models and conceptualisations) are not yet addressed in Brazilian field experiments.

Experimental studies in the Amazon have contributed to a better understand of (i) hydrological processes (FRANKEN et al., 1986; HODNETT et al., 1997; WICKEL; GIESEN; SÁ, 2008); (ii) impact of LUCC (CHAVES et al., 2008; DIAS et al., 2015; MARKEWITZ et al., 2001); (iii) energy balance closure (GERKEN et al., 2018); (iv) spatial distribution of key hydrological parameters (CUARTAS et al., 2012); (v) organic carbon fluxes (JOHNSON et al., 2006; WATERLOO et al., 2006), and soil water dynamics under different conditions of seasonal rainfall variability in that biome (BROEDEL et al., 2017).

In semi-arid zones, the main focus has been on rainfall characteristics, runoff generation, and sediment production (BARBOSA et al., 2018; CADIER, 1996; SRINIVASAN; GALVAO, 1995). The hydrological implications of reforested areas were mainly studied in south-eastern Brazil (ALMEIDA et al., 2007; ALMEIDA; SOARES, 2003; GARCIA et al., 2018; SMETHURST; ALMEIDA; LOOS, 2015). Monitoring activities in the Brazilian semi-arid region over the past decades have been the basis of our current understanding about runoff generation and water availability in such severe environments (CADIER, 1996; FIGUEIREDO et al., 2016; SRINIVASAN; GALVAO, 1995; TIECHER et al., 2017). Those studies provide insights on the surface-water scarcity of the Caatinga biome. The semi-arid zone is seen as one of the top-ranked systems deserving more attention and aiming to improve our understanding of hydrological processes (BLUME; MEERVELD; WEILER, 2017). However, such systems have hosted less field experiments than others (BURT; MCDONNELL, 2015); hence, EBR in the Brazilian Caatinga become even more relevant in that context.

The 10 representative basins (43 micro-basins) resulting from the cooperation between SUDENE and ORSTOM are paramount to begin to understand the runoff processes in the Brazilian semi-arid region. Those pioneering studies revealed a strong interannual irregularity in runoff. According to Cadier (1996), once every three years runoff remains below half the long-term average and is almost null every 10 years. Results from the monitoring of the Aiuaba basin, in Ceará state, showed that the annual runoff coefficient fell below 0.5% and discharge at the outlet only occurred four days per year on average. The most relevant variables to explain runoff initiation in the semi-arid region are total precipitation and maximum 60-min rainfall intensity. It is possible that surface-flow initiation in the Caatinga biome is strongly influenced by root-system dynamics, which changes macro-porosity of the soil and therefore its initial abstraction (FIGUEIREDO et al., 2016).

Figure 4 – Unsolved problems in hydrology addressed by Brazilian EBR



CONCLUSION

The main hydrological variables monitored in the EBR studied in this report include: P, Q, SM, GW, SE, ET, WQ. P and Q were the most commonly monitored variables. Conversely, WQ parameters and SE were measured in less than 50% of the EBR. Field hydrology studies in Brazil have barely started compared to those in the United States and Europe. In addition, communication of the achieved results and analyses have been mostly limited to publications without international impact; only a relatively low number of studies were found in peer-reviewed journals. In some cases, this fact seems to be related to insufficient monitoring periods and low numbers of monitored variables (basically rainfall and streamflow). However, a short period of observation, despite being a limiting factor, is not a decisive one.

Regardless of these particularities, we found that an essential factor in busting field-hydrology-related productivity is the financial support of the Federal Government. Between 2002 and 2013, when a large number of resources were invested in research, the number of MBs doubled, and the number of published studies tripled. Once those investments ceased, the number of new MBs decreased, and scientific productivity has oscillated ever since.

Based on our review, the soil moisture content, water quality, sediment transport, and erosion are poorly monitored in the MBs catalogued in this study;

Field-based studies in Brazil have contributed to a better understanding of the hydrological processes in humid and semi-arid regions, as well as how these processes interact with agricultural activities and human interference in general. People interested in using or producing hydrological ground-based data may ask themselves the questions raised in the Introduction and find answers throughout this paper. Therefore, this review offers a long-term reference for future field hydrology studies, especially in Brazil.

This paper is also an attempt to improve the knowledge of in situ field studies. For this purpose, we propose the creation of a national network of MBs to promote data standardisation, data exchange, transfer, and publication. The exchange of experience between Brazilian researchers and the international community could move EBR to the next scientific step by promoting better understanding of hydrological variables in different climatic regions. Moreover, as mentioned before, international partnerships often result in publications with greater impact. Taking into account that most studies (~80%) are published in local journals, collaborative partnerships should be encouraged to increase the reach of our findings in the international community.

Although there is a consensus about the importance of field hydrology experiments (BLUME; MEERVELD; WEILER, 2017), there is also an imbalance between "outdoor" and "indoor" hydrologists, that is, those doing the monitoring and those who wish to use the data collected (ALLEN; BERGHUIJS, 2018). In this sense, we share the opinion of (BLUME; MEERVELD; WEILER, 2017) in that the greatest challenge for field hydrology is the maintenance of monitoring networks; which is why one of this paper's intents is to foment the creation of a national network. Interruption of monitoring activities should be avoided at all costs, whereas maintaining EBR as active, especially those with long historical records, should be encouraged.

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