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Environmental damage of urbanized stream corridors in a coastal plain in Southern Brazil

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ABSTRACT

The implementation of sustainable spaces and infrastructure can offset environmental damage caused by urban land parceling of coastal plains. However, there is no clear methodology for the analysis and quantification of damage on coastal water bodies. In this paper, we provide a procedure for the identification of degraded urban rivers and the quantification of corresponding environmental damage according to Brazilian law. In Brazil, environmental legislation requires public authorities to consider the recovery or compensation of environmental liabilities in protected areas in the regularization of urban occupations. We use the Jurerê Coastal Plain located in Southern Brazil as a case study to analyze damage to the river bed and the riparian permanent preservation area (PPA). The suppression of the Meio and Faustino rivers occurred in several stages starting in the 1970s. Our analysis is subdivided into: (i) review of the evolution of environmental legislation protecting streams corridors over time; (ii) spatio-temporal analysis of land use from historical cartographic documents, obtaining accurate topographic data to assist in the identification of the river beds; and (iii) quantification of the suppressed PPA according to the legislation in force at the time of the implementation of urban land parceling. The procedure developed here contributes to the quantification of the environmental liabilities of other urban occupations and may be used to determine the compensatory environmental measures which are effectively bound to the corresponding damaged area.

1. Introduction

Most rivers around the world have been altered by human action (Grill et al., 2019; Belletti et al., 2020), the effects of which have spread for decades or centuries (Wohl and Merritts, 2007). In coastal zones, the occupation alters landscapes and is usually driven by the urban land parceling. One of the main impacts of land use conversion is altering the natural flow of surface water and creating true urban river deserts (Napieralski and Carvalhaes, 2016). Due to climate change and rapid urbanization, vulnerability to the risk of flooding has increased in recent decades (Duan et al., 2016) and the environmental quality of cities has decreased. The rehabilitation, protection and conservation of coastal ecosystems require management that considers the integrated analysis of ecosystemic and socioeconomic elements, constituting a challenge and, at the same time, an opportunity for coastal management (Scherer and Asmus, 2016; Silva et al., 2019).

Many urban settlements have also impacted environmentally protected areas, requiring interventions to correct the damage generated by urbanization (Silva, 2018; Moschetto et al., 2021). The restoration of small urban rivers has led to improved water quality (McMillan and NOE, 2017), which is also observed in several nature-based solutions implemented in Europe. These solutions include the creation of green spaces, wetlands and other sustainable infrastructure for management water (cf. Oral et al., 2020). In Finland, for example, it has been shown that there is public support for such measures and people are willing to invest in the environmental recovery of their streams (Sarvilinna et al., 2016). Moreover, several cities in the world have taken the initiative for adapting to climate change, with emphasis on the creation,

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maintenance, and recovery of urban green areas, whether from the perspective of risk analysis or urban regeneration and sustainability (García Sánchez et al., 2018; Papatheochari and Coccossis, 2019). These are important planning tools to satisfy the environmental, social and economic needs of urban areas (Sturiale and Scuderi, 2019).

It is estimated that 89% of the wetlands in South America were lost after 1900 (Creed et al., 2017) while 20% of the Brazilian territory is still covered by them (Junk et al., 2013). The occupation of coastal areas is a worldwide trend and about 26% of the Brazilian population is concentrated in coastal zone municipalities (IBGE, 2011, 2016). Brazilian cities, especially in the coastal zone, were built on environmentally protected areas. In order to adapt irregular urban occupations, the instrument of land regularization of urban settlements was created in Brazil. Those instruments aim to guarantee the social right to housing, the full development of the social functions of urban property and the improvement of urban and environmental conditions (Brasil, 1988, 2009, 2017), which can be integrated with coastal management.

Environmental damage can be regarded as an undesirable change in any of the natural resources, affecting nature and society, in that it violates the fundamental right of everyone to balanced environment (Leite, 2015). In Brazil, it is not subject to a statute of limitations (Brasil, 2020), so land use studies need to identify environmental liabilities and quantify the PPA occupied for recovery or compensation, which is a form of indemnity.

Brazilian law defines *stream corridors* as permanent preservation areas (PPA) due to their roles as ecotones between aquatic and terrestrial environments. Originally, only land regularization for low-income occupations (i.e., social interest) was allowed in a permanent preservation area. The Law No. 12651, 2012, made it possible to apply this instrument to other forms of urban occupation (i.e., specific interest) in PPA, while there should be maintained a nonbuildable strip along watercourses with a minimum width of 15 m on each side (Brasil, 2012). However, in order for this legal exception not to be used indiscriminately it is necessary that environmental liabilities are identified and the environmental functions of the suppressed protected spaces restored.

A common feature in several countries is the change in environmental regulations over time, the dynamics of which can be seen in the evolution of Brazilian legislation for protected areas. The precise identification of the evolution of the occupation of an urban nucleus in a PPA over time allows the quantification of the environmental damage, according to the legislation in force in each period. That identification can be used for the environmental recovery of urban rivers or, in the hypothesis that the reversal of the damage is not possible, it could be used to define alternatives offsets to ensure the improvement of the degraded environment, such as the creation of protected areas not only focusing on ecosystem functions, but also as tools for the adaptive capacity and resilience of coastal settlements to climate change (Ferro-Azcona et al., 2019).

In this paper, we provide a procedure for the identification of PPA and further environmental damage quantification according to Brazilian law, which can be applied to other urban occupations on protected areas throughout the Brazilian coast, as well as in countries that have similar legislation. The procedure adopted to quantify environmental damage can be subdivided into the following steps: (i) review of the evolution of environmental legislation protecting streams corridors over time; (ii) spatio-temporal analysis of land use from historical cartographic documents, obtaining accurate topographic data to assist in the identification of the river beds investigated; and (iii) quantification of PPA suppressed due to the legislation in force at the time of the implementation of urban land parceling. We use the Jurerê Coastal Plain located in Southern Brazil as a case study to analyze damage to the PPA of the Meio and Faustino rivers, whose suppression occurred in several stages from the 1970s.

2. Study area

The study area covers the permanent preservation areas of the Faustino and Meio rivers, located in the coastal plain of the Jurerê neighborhood, on Santa Catarina Island, in the municipality of Florianópolis, Brazil. It is bounded to the north by the coast line, to the east by the SC 402 highway and the Jurerê hill, to the south by the SC 400 highway and to the west by the base of the Forte hill (Fig. 1). The outlet of the Faustino and that of the Meio river formed an intermittent bar that could suffer momentary interruptions.

The coastal plain under study is predominantly sandy, formed by marine regressions and progressions, constituting a restinga ecosystem, with humid areas and several water bodies. According to studies of nearby areas, it is a coastal plain of recent formation (Hein et al., 2016). Sea level variations over the last 7500 years have been determinants for defining the current shoreline, the formation of paleolagoons and marshes in those coastal sedimentary landscapes (Castro et al., 2014; Cunha et al., 2017; Cooper et al., 2018). It is an area sensitive to climate change due to its low topography (ranging from zero to 11.89 m of elevation, with an average of 2.86 m), reduced average slopes (2.39%) and recently observed tides have reached 1.75 m above mean sea level.

3. Materials and methods

3.1. Evolution of stream corridor protection in Brazilian environmental law

Permanent Preservation Area (PPA) is defined in Brazilian law as a protected territorial area, whether or not covered by native vegetation, with the environmental functions of preserving water resources, the landscape, the geological stability and the biodiversity, they should facilitate the genetic flow of fauna and flora, protecting the soil and guaranteeing the welfare of human populations (Brasil, 2012). The stream corridors are considered as PPA by the law, but the widths of the protected areas on the banks of watercourses have been modified with the evolution of Brazilian environmental legislation over time. Therefore, environmental regularization of urban settlements requires the analyses of the protected area according to the enforced law at the date of the installation of each urbanized portion.

The first Brazilian Forest Code defined *protective forests* as those intended to conserve the water regime and prevent erosion by the action of natural agents and whose conservation should be perennial (Brasil, 1934). Even though vegetation on the banks of watercourses fits that definition of protective forests, the Forest Code of 1934 did not set the preservation limits for marginal vegetation. The Forest Code of 1965 revoked the previous order and was explicit in establishing that the PPA of any watercourse should be equivalent to half of its width, respecting the minimum value of 5 m and the maximum of 100 m (Brasil, 1965). Thus, from January 14, 1966 (i.e., the effective date of the 1965 Forest Code), the permanent preservation area of marginal vegetation along any type of watercourse was to be set according to the width of the river channel. Fig. 2 summarizes the evolution in time of the minimum width defined as APP of marginal vegetation along watercourses since the 1965 Forest Code.

In 1986, new limits for the PPA on the banks of watercourses were set to vary according to the dimensions of the river bed cross section, ranging from a minimum of 30 m to the value equal to the width of the river bed (Brasil, 1986). The dimensions of the PPA were changed once again in 1989. The new maximum enforced width of the marginal band could reach 500 m while the minimum remained 30 m (Brasil, 1989). The values set for permanent preservation ranges have remained unchanged in the current Native Vegetation Protection Law (Brasil, 2012), also known as the 2012 Forest Code. Thus, to identify and quantify the damage caused by urban occupations in PPA on stream corridors, the following periods were considered in the spatio-temporal analysis of land use: (i) until January 13, 1966; (ii) from January 14, 1966 to July 7,

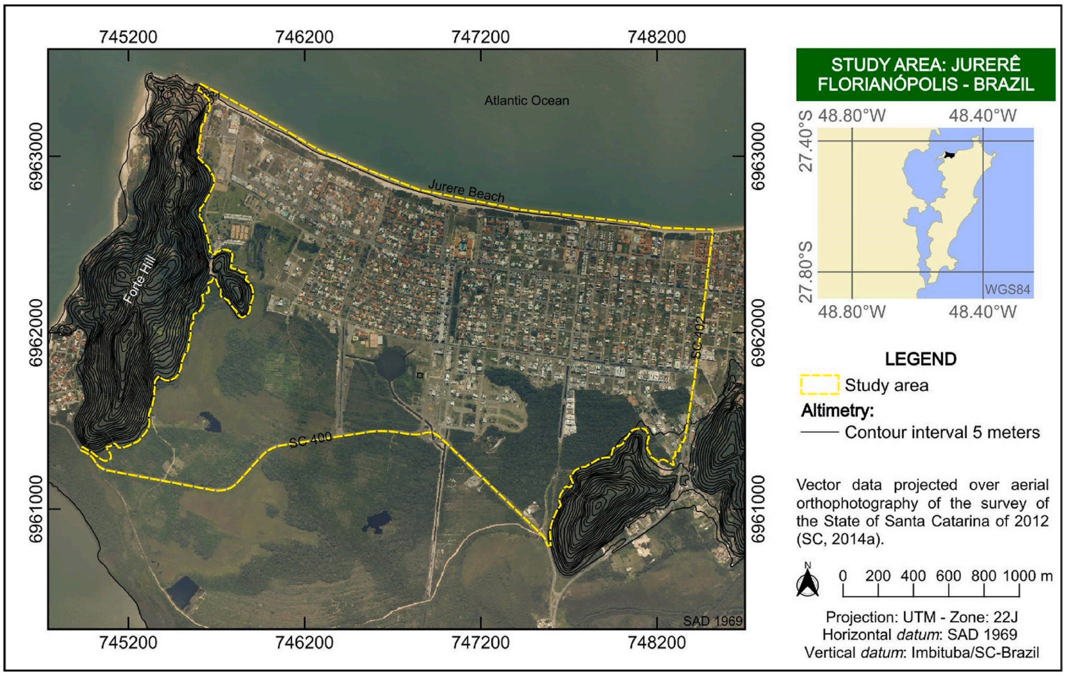

Fig. 1. Delineation of the study area. Data obtained from IPUF (2002a) and SC (2014a).

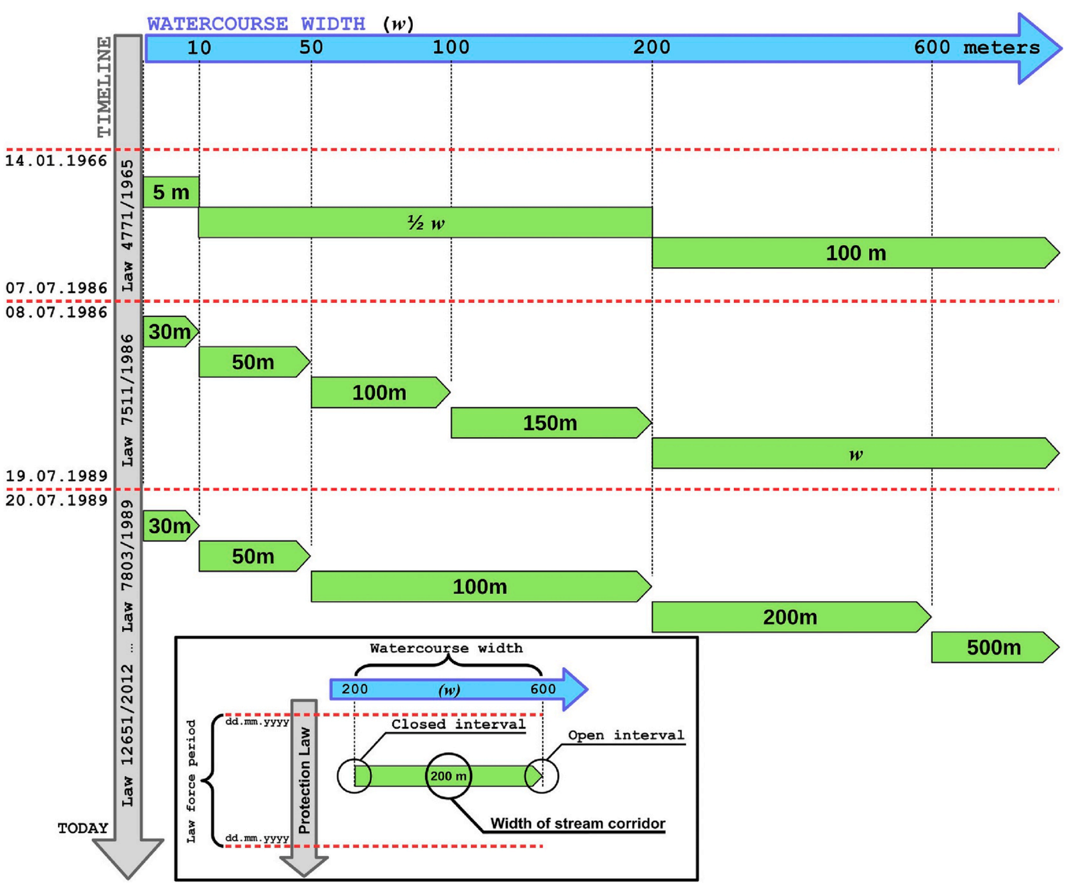

Fig. 2. Evolution of stream corridor protection in Brazilian environmental law.

1986; (iii) from July 8, 1986 to July 19, 1989; and (iv) from July 20, 1989 to the present day.

3.2. Spatio-temporal analysis of land use

River bed and stream corridors impacted by urbanization were identified by reconstituting the original topography of the study area.

Historical data (e.g., aerial photographs, orbital images, maps and topographic plans) were analyzed employing photogrammetry, remote sensing and topography techniques. Remote sensing techniques are useful for identifying the original situation of degraded areas (Costa and Reis, 2017; Meroni et al., 2017) and urban water bodies (Yang et al., 2015; He et al., 2017; Costa and Reis, 2017), including tidal coastal plains (Tseng et al., 2017). The following documents instructed the analysis of land use and the identification of suppressed rivers beds:

- Aerial photographs from 1938 (scale 1:37000), 1957 (scale 1:25000), 1966 (scale 1:60000), 1977 (scale 1:25000), 1994 (scale 1:35000), 2002 (scale 1:5000) and 2011 (scale 1:2000);
- Nautical Chart 1903 (North Channel of Santa Catarina) - Surveys 1954/1955, on the scale of 1:50075;
- Topographic charts of the Florianópolis Urban Planning Institute (IPUF): sheets SG22ZD–II–4-SE-D and SG-22-ZD–III–3-SO-C from the 1979 planialtimetric survey, both on the scale of 1:10000;
- Topographic charts of the Brazilian Institute of Geography and Statistics (IBGE): sheet SG-22-ZD–II–4 (Biguaçu), produced in 1974, and sheet SG-22-ZD–III–3 (Canasvieiras), produced in 1981, both with a scale of 1:50000;
- Blueprints with the topographic surveys and the design of the longitudinal profiles of the streets approved by the Municipality of Florianópolis in the years 1982, 1983 and 1984, in the horizontal scale of 1:1000 and the vertical scales of 1:100;
- Orbital images of the Landsat 5 satellite, orbit 220, point 79, of April 23, 1986 and May 14, 1989;

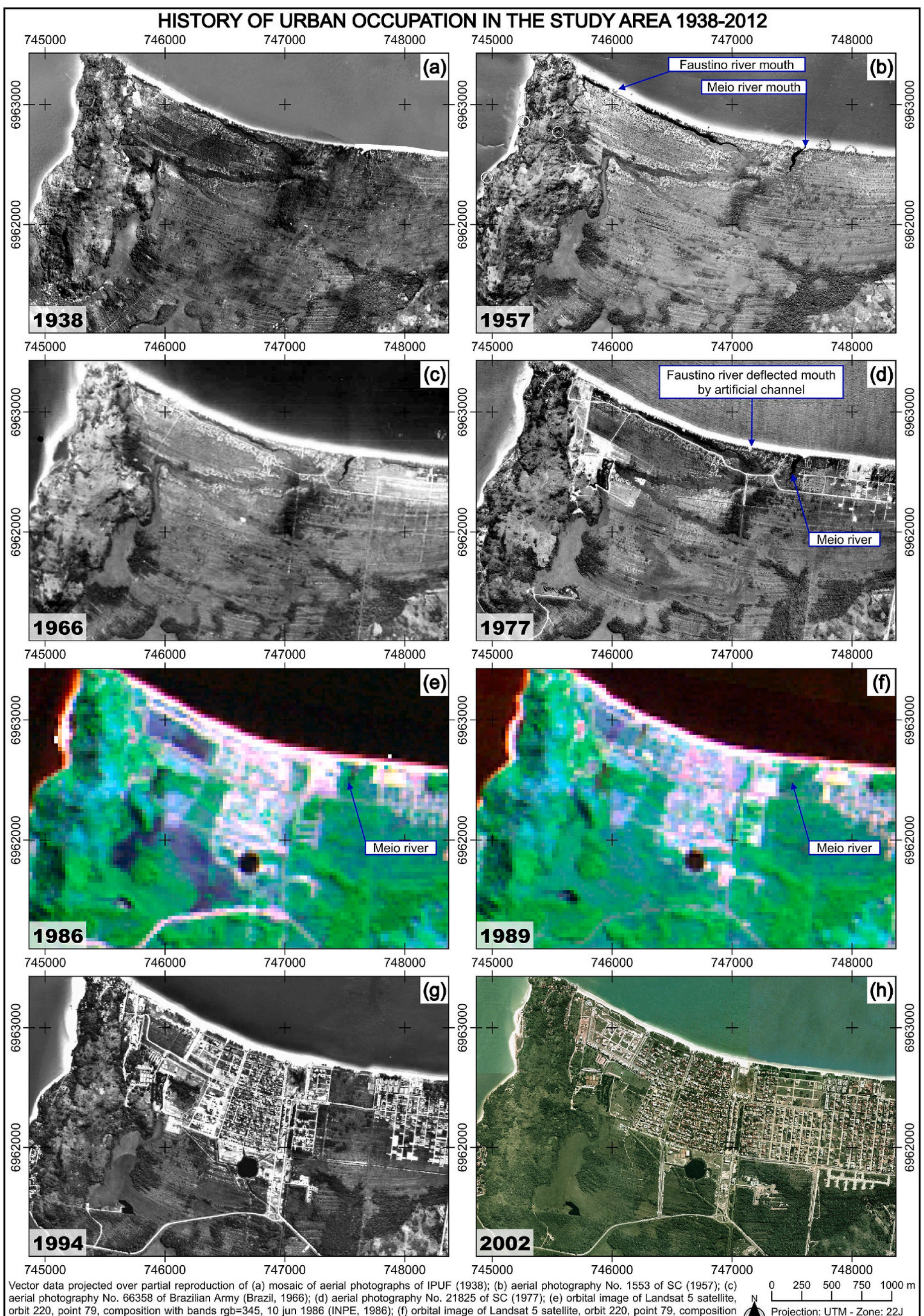

Fig. 3. Historical occupation of the study area. (a) 1938, (b) 1957, (c) May 16, 1966, (d) 1977, (e) Jun 10, 1986, (f) May 15, 1989, (g) 1994 and (h) 2002. Data obtained from SC (1938, 1957, 1977), Brasil (1966), INPE (1986, 1989), and IPUF (1994, 2002b).

- Topographic charts of the aerial survey of the city of Florianópolis (2002), in the scale of 1:2000;
- Digital terrain model of the Santa Catarina State Survey 2010–2012, sheets SG-22-Z-DII4-SE-D and SG-22-Z-D–III–3-SO-C, in the scale of 1:10000, published in 2014;
- Orbital image of the China-Brazil earth resources satellite CBERS 4, orbit 155, point 131, provided by INPE, whose orbit occurred on October 18, 2017.

All orbital images, aerial photographs and mosaics were rectified and georeferenced to the datum SAD 69, the same of the 2002 IPUF cartographic base (1:2000 scale) which is the most accurate cartographic base available and was, therefore, used as reference. Analyzing the historical series of aerial photographs and orbital images, it can be observed that from the 1970s the coastal plain underwent several anthropic interventions that completely altered its topography (Fig. 3). The urban land parceling over the Faustino River bed and banks began in 1975 at the west end of the seafront. After July 7, 1982 this parceling was intensified due to the approval of the Municipality of Florianópolis for the installation of successive subdivisions identified in the original blueprints of the urban street designs.

From 1977 to 1994, the State of Santa Catarina did not carry out aerophotogrammetric surveys, so for the purpose of identifying the areas implemented in this period, we correlated the development projects approved in Florianópolis with orbital satellite images *Landsat 5*. In principle, initial land parceling activities were concentrated before June 10, 1986. Between June 10, 1986, and May 14, 1989 there is no noticeable changes (Fig. 3e and f) as can be seen in the satellite images *Landsat 5* (INPE, 1986, 1989). Therefore, there are two periods to be considered for the spatio-temporal determination of the marginal PPA of the watercourses:

- Period prior to July 7, 1986: protected area defined by the original wording of art. 2, item “a”, of Law No. 4771, 1965;
- Period after July 20, 1989: protected area defined by art. 2, item “a”, of Law No. 4771, 1965, with wording given by Law No. 7803, 1989, sustained by art. 4, item I, of Law No. 12651, 2012.

Due to limitations in resolution of the orbital images for the period from July 8, 1986 to July 19, 1989, any changes in this period were considered prior to July 7, 1986. Restinga ecosystems that naturally regenerated on the Jurerê beach and the public sidewalks were not considered as a consolidated area.

For the most inland banks of the Faustino River, it would be ideal to have cartographic material prior to the 1970s to indicate the flood plain’s dimensions with metric precision, which would allow the analysis of the situation of that site before anthropic interventions by urbanization. However, no cartographic material with the desired vertical accuracy was found for that period. Alternatively, we sought to accomplish this task by generating digital elevation models from stereoscopic pairs of high-resolution aerial photographs. We searched the Santa Catarina State Statistics and Cartography Directorate for aerial photographs whose subject matter incorporated the area of study. The following available photographs were digitized with a resolution of 42.33 μm:

- 1938 Survey: photographs No. 18, 20, 22 and 143, all on the scale of 1:37000;
- 1957 Survey: photographs No. 1550, 1551, 1553 and 1554, all on the scale of 1:25000;
- 1977 Survey: photographs No. 21822, 21823, 21824, 21825, 21827 and 21828, all on the scale of 1:25000.

Considering that the 1977 aerial survey photographs served as the basis for the 1979 IPUF planialtimetric survey, and the fact that the pair of photographs No. 21825 and 21827 retained an approximate coverage of 60%, it was possible to form a stereoscopic pair between them for terrain visualization purposes. The dimensions of the original terrain were obtained using the *e-foto* software, which constitutes an educational digital photogrammetric station in an open source environment (Mota et al., 2012). Due to the effective scale of the 1977 photographs, approximately of 1:30000 (nominal scale is of 1:25000), and the resolution of the digitized material (42.33 μm), it was not possible to generate a digital surface model with the required vertical accuracy of 1 m or less. However, it was possible to use analogical visualization through mirror stereoscope, as well as to obtain digital three-dimensional terrain visualization through an anaglyph, which is a useful tool for photointerpretation (Ebert, 2015; Quirogaa et al., 2015).

As an alternative to obtain the elevation of parts of the pristine terrain, we used the blueprints approved by the Municipality at the time of the land parceling, whose longitudinal profiles inform the terrain dimensions in the situation prior to the settlement installation (1982), as well as the designed elevation. Those profiles have been digitized and georeferenced in relation to the horizontal SAD 69 and vertical Imbituba datums (see supplementary material).

3.3. *Quantification of environmental damage*

The respective PPA for the identified rivers beds were generated for each normative period according to Fig. 2. The time of implementation of each stage of land subdivision was considered as when roads could start to be identified in the aerial photographs or orbital images, since it characterizes the beginning of the installation of an allotment (Silva, 2018). Finally, land use analysis and the evolution of legal protected areas over time were used to quantify the environmental damage in accordance with the legislation in force at the time of land parceling.

4. Results and discussion

4.1. *Identification of the Meio and Faustino rivers beds*

The Meio and Faustino rivers are identified in various cartographic documents and historical aerial photographs. The watercourses could be identified in the interior of the Jurerê plain in the Nautical Chart No. 1903 (Brasil. Marinha do Brasil, 1954). In this cartographic material, the Faustino River source is a flooded area located in the southwest portion of the plain with a tributary that crosses the plain transversely from east to west (Fig. 4a). The Santa Catarina Island Geological Map of 2014 reports the existence of paludial deposits in places where the old Faustino River bed was located and coincide with the flooded area indicated in the 1954 Nautical Chart (Fig. 4d). Those paludial deposits (HPp) consist of peat or fine sediments, rich in organic matter, located in depressions, forming semi-flooded areas (Tomazzoli and Pellerin, 2014). They are located in the southwestern portion of the plain and also in an area near the river mouth.

In the IBGE database the rivers under study are depicted in two charts covering the area under analysis: sheet SG-22-ZD–II–4 (Biguaçu), produced in 1974, and sheet SG-22- ZD–III–3 (Canasvieiras), produced in 1981, both with a scale of 1:50000, reproduced in Fig. 4b. The oldest available planialtimetric survey, with adequate accuracy (1:10000 scale), is the one elaborated in 1979 using the 1977 aerial survey, which also shows the rivers under study (Fig. 4c). The original connections of the Faustino and the Meio rivers to the sea can be seen in the aerial photographs of 1938 and 1957 (Fig. 3a and b). These connections are also depicted on sheets SG-22-ZD–II–4 (1974) and SG-22-ZD –III–3 (1981), from IBGE, and in sheets SG22-ZDII-4-SE-D and SG-22-ZD–III–3-SO-C, from the 1979 IPUF planialtimetric survey. In summary, the Nautical Chart (Brasil. Marinha do Brasil, 1954), the IBGE Topographic Charts (IBGE, 1974, 1981) and the IPUF Charts (IPUF, 1979) depict the Faustino River, the Meio River and other watercourses located at the east and west ends of Jurerê Beach.

Cartographic documents and aerial photographs allow to describe

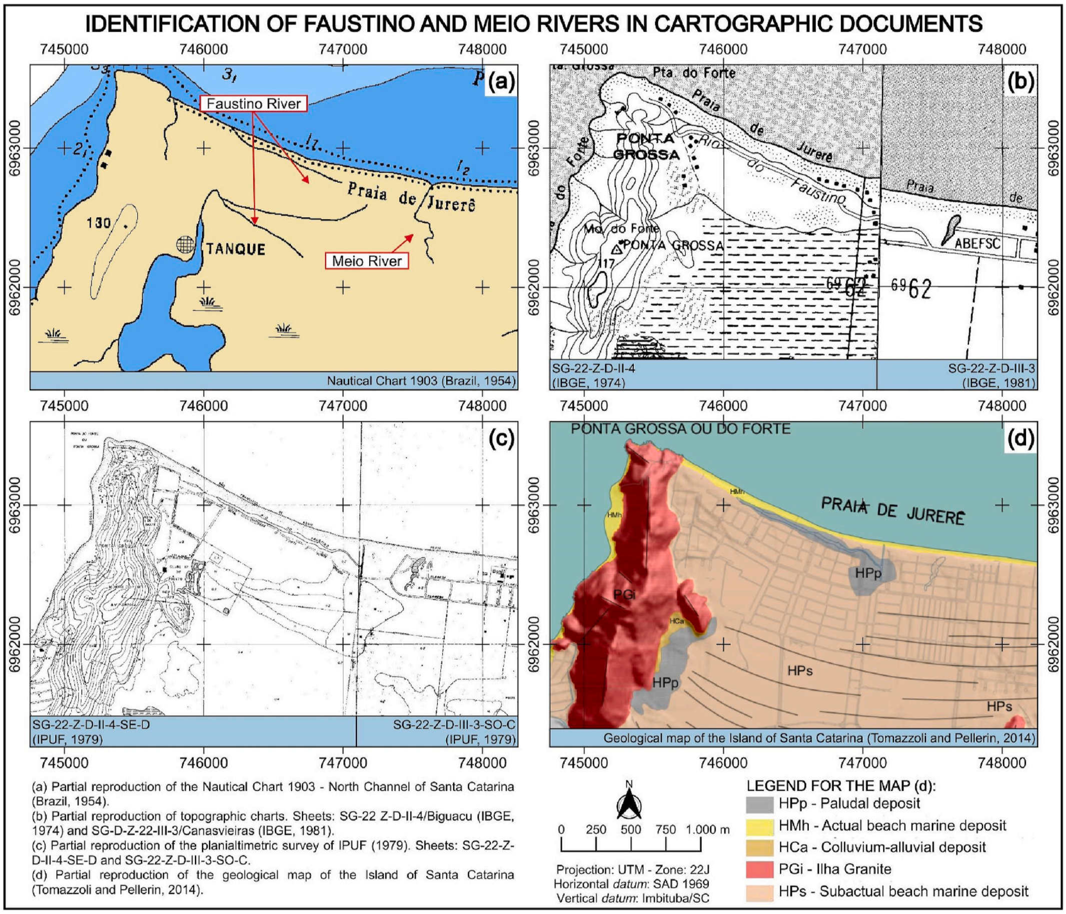

Fig. 4. Cartographic documents that depict the Meio and Faustino Rivers. (a) Nautical Chart 1903 - North Channel of Santa Catarina (Brasil. Marinha do Brasil, 1954). (b) Topographic charts of the IBGE (1974, 1981). (c) Planialtimetric survey of IPUF (1979). (d) Geologic map of Santa Catarina Island (Tomazzoli and Pellerin, 2014).

the transformations of the rivers under study from their pristine condition to the suppression of their beds and marginal protected areas. It can be seen that the Faustino and Meio rivers beds are still preserved in 1957 (Fig. 3b). From 1966 (Fig. 3c) the installation of the first canals for drainage of the wetlands of the plain can be observed, initiating a gradual process of alteration of the natural drainage network. Up to 1974 (Fig. 4b) the changes were not yet significant, but by 1977 the natural drainage of the Jurerê Plain was completely altered (Fig. 3d). The Faustino River, the main water body of that plain, is no longer connected with the sea. The Meio River still preserved its mouth by the ocean, but by the time the photograph was taken, the mouth was naturally interrupted at the sea shore.

The points generated from the analysis of the longitudinal profiles of the urban nucleus blueprints helped in the photointerpretation and identification of the Faustino River. For places not covered in those blueprints, the geological indications (i.e. Tomazzoli and Pellerin, 2014) and the altimetric data available from the planialtimetric surveys and digital elevation models (IPUF, 1979, 2002a; SC, 2014b, 2014c) were used for the river bed delimitation. The natural drainage network was identified and delimited having as historical reference the aerial photograph of 1957 (Fig. 6).

The aerial photographs, orbital images, topographic maps and the allotment blueprints available in the municipal records show that the Faustino and Meio rivers had their beds definitively suppressed by the land parceling and ancillary works from the decade of 1980 (Fig. 3e and f). The Meio River can be easily observed in the aerial photographs of 1957 and 1977 (Fig. 3b and c), however, by 1994 it had already been filled for the later implementation of the allotments (Fig. 3f). The alteration of the natural river drainage network of the studied rivers was completed in the 1994 aerial photograph (Fig. 3g). In the orthophotographs of 2002 the allotments are implemented (Fig. 3h). The Faustino and Meio rivers no longer exist, except for some small remaining portions of the beds.

Originally, the waters within the plain were drained to the beach of Jurerê (to the north). The natural drainage network has been modified through artificial canals which are currently transported towards the mangrove swamp of Carijós Ecological Station (to the south), as shown in Fig. 5.

4.2. Delineation of the permanent protected areas

Considering that the obligation of reparation of environmental damage is not subject to a statute of limitations, for the purpose of delineating the watercourse beds and their respective PPA, the oldest historical data was used. The consolidated urban areas are those that are built or with an apparent effective layout (e.g., streets are visible, as they characterize the initial implementation of the allotments) in the photographs and images. The urbanization of the land under analysis began after 1974 and intensified after 1982. As for the Faustino River bed PPA, the implantations of the various stages of the urban nucleus were concentrated in two significant normative periods: before July 7, 1986, during the term of Law No. 4771, 1965, in its original wording, and after July 20, 1989, when the amendments given by Law No. 7803, 1989, which were repeated by Law No. 12651, 2012 (currently in force). Specifically, for the Meio River bed and PPA, the implementation of the allotment (i.e., through the effective street layout) occurred after July

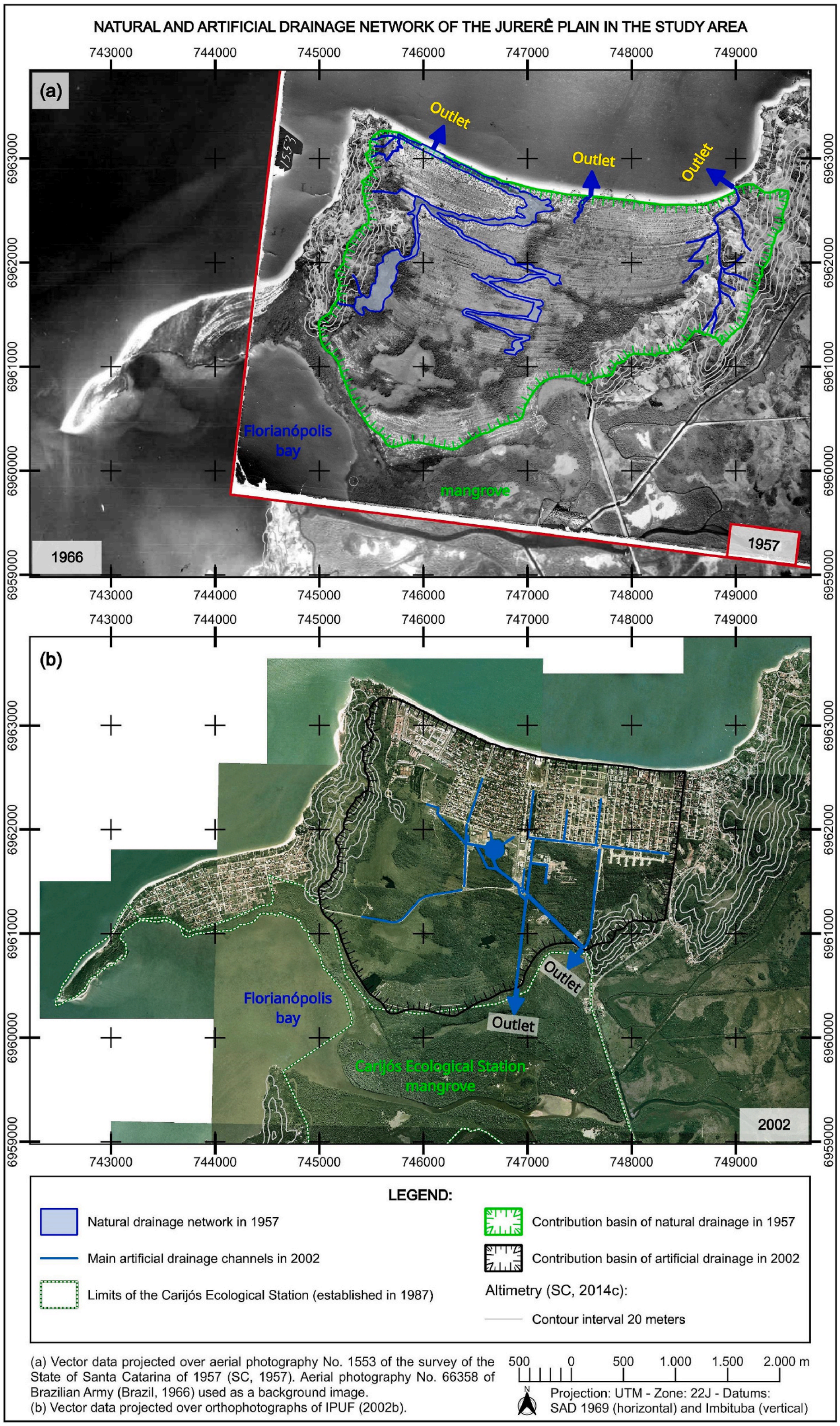

Fig. 5. Drainage network and contribution basin changes in the study area. (a) Natural drainage in 1957. (b) Current drainage, consolidated in 2002 by the implementation of artificial canals during urbanization. Projected results for aerial photography of SC (1957), Brasil (1966), and IPUF (2002b).

20, 1989.

Once the areas occupied by the urban nucleus were identified and the location of the suppressed river beds was known, it was possible to quantify the PPA object of urbanization in each period. The PPA of the Meio, Faustino and tributary rivers partially overlap, so the intersection analysis of protected areas was performed to quantify environmental damage. Fig. 7 and Table 1 show the PPA of the suppressed beds and stream corridors of the Meio, Faustino and tributaries in each period according to the environmental legislation before and after the facts.

The environmental damage caused by the suppression of the rivers

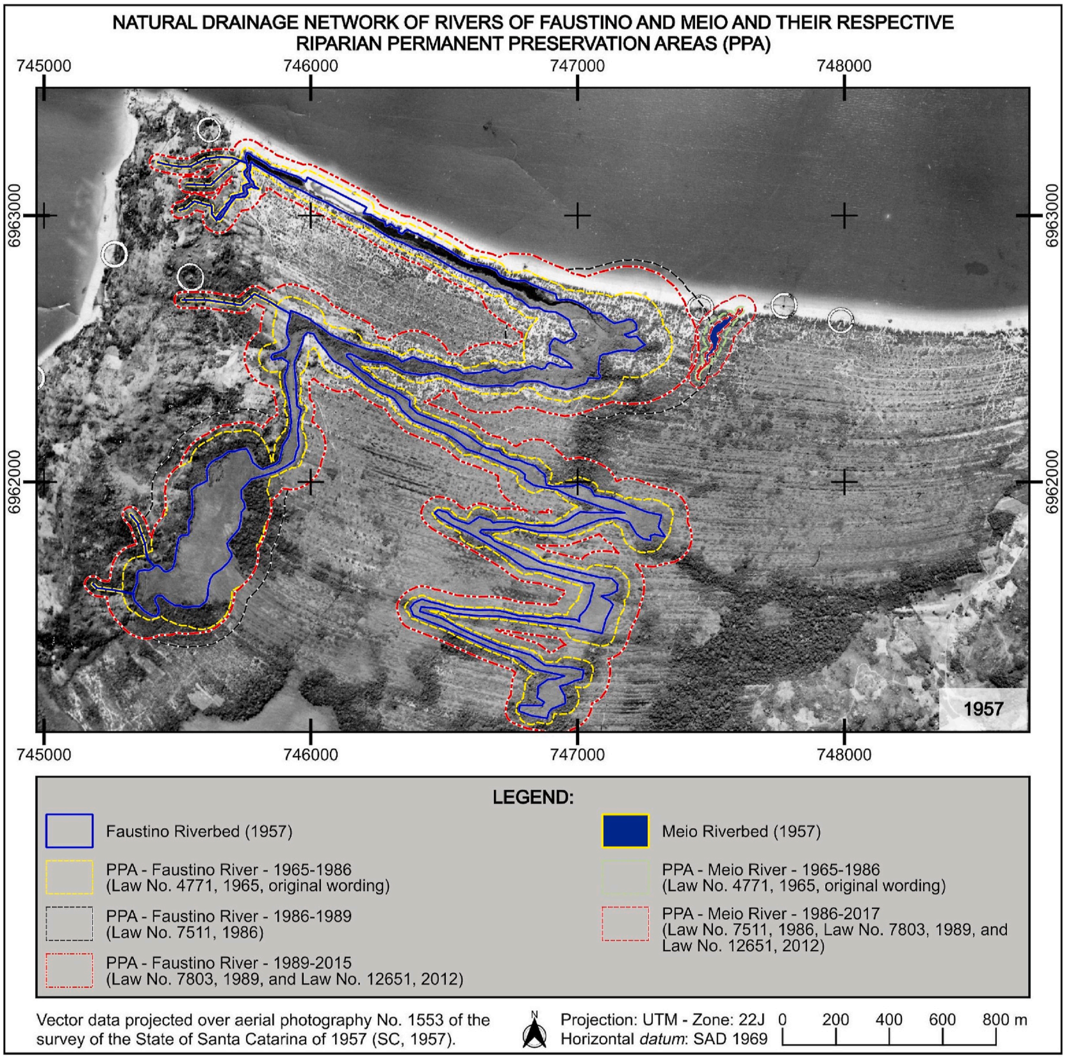

Fig. 6. Natural drainage of the rivers Meio, Faustino and its tributaries in 1957. Permanent preservation areas (stream corridors) of according to the evolution of environmental legislation. Projected results on aerial photography of SC (1957).

beds under study corresponds to an area of 28.02 ha. Considering the protected stream corridor in accordance with the legislation in force at the time of each phase of installation of the urban nucleus, the damage in PPA is equivalent to 25.65 ha (before 1986) and 26.55 ha (after 1989), whose environmental damage was suppressed (bed and PPA) corresponds to a minimum area of 80.22 ha. If the environmental liability prior to 1986 were analyzed using the PPA defined in the current legislation (Law No. 12651, 2012), the total area to be compensated would be 116.01 ha.

4.3. Compensatory environmental measures

In the present paper, it was observed that the natural drainage of the study area was artificially altered, through the diversion of surface waters and urban drainage from the settlements to the interior of the Carijós Ecological Station (ESEC Carijós) mangrove (Fig. 5). Urban drainage water can contain numerous chemical pollutants harmful to the environment and public health (Finotti et al., 2015; Duan et al., 2018; Santos et al., 2020) and, in the case of ESEC Carijós, water quality is directly associated with physical characteristics and urbanization of the contributing river basins, being mainly influenced by the tidal regime, population density, sanitation rates and the flow of affluent rivers (Rodrigues, 2016).

The main objectives of the ESEC Carijós are to preserve the largest mangrove remnants on the Santa Catarina Island and carry out scientific research. This constitutes one of the most restrictive categories among Brazilian protected areas, which does not even allow public visitation (except for educational purposes). However, despite its extreme biological importance and all the environmental services it provides, it suffers from the strong pressure of urban expansion. Therefore, it is required the development of strategies to discuss the use of the areas in its buffer zone, aiming to minimize the environmental impacts to that protected area and neighboring populations (e.g. Figueiroa and Scherer, 2016; Figueiroa et al., 2020).

In the immediate surroundings of ESEC Carijós there are many fragments of transitional vegetation remnants between mangrove and restinga ecosystems. However, the legal protection of these areas is still very fragile, due to the difficulty of defining these environments. To compensate for the environmental impacts for ESEC Carijós, a management measure to be adopted may be the transformation of transition ecosystems into private lands in Private Reserve of Natural Heritage (category of private Brazilian protected area with the objective of perpetually conserving diversity biological) or the donation to the government to expand the ESEC or establish new public protected areas.

To compensate for the riparian habitats lost in the Faustino and Meio rivers, improve the quality of surface water that flows into ESEC Carijós and, at the same time, create sustainable infrastructure to mitigate inundation caused by storm water and meteorological tides, the

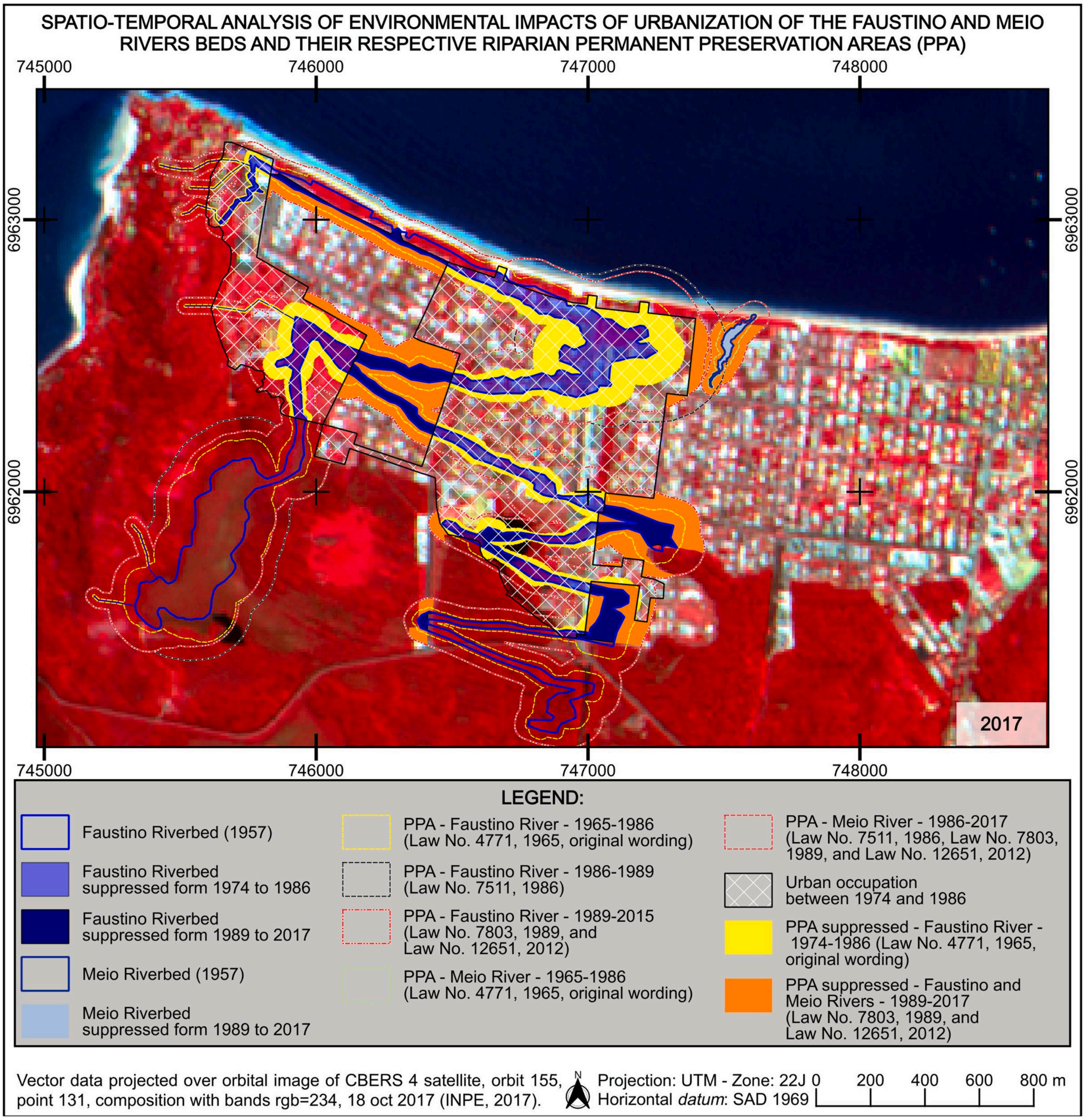

Fig. 7. Spatio-temporal analysis of the bed and PPA occupation of the Meio and Faustino Rivers in Jurerê, considering the legislation in force at the time of execution each phase of the layout of land parceling. Projected results on orbital imaging of INPE (2017).

adoption of nature-based solutions can be considered by the implantation of forested riparian corridors on the margins of the current anthropized river channels (Sarvilinna et al., 2016; McMillan and NOE, 2017) and artificial wetlands (Stefanakis, 2019; Oral et al., 2020).

5. Conclusions

The process of environmental regularization of urban settlements, when incorporated into coastal management, can be a special opportunity for the implementation of measures to compensate and mitigate the environmental impacts generated by irregular urban occupation. Improvements to the affected ecosystems and people must be done through compensatory measures that provide environmental gains corresponding to the identified degraded area.

In the case of the present study, it was found that the land parceling in the locality of Jurerê (Florianópolis, Brazil) implied the suppression of the Meio River, Faustino River and some tributaries. The case portrays a common form of occupation of tourist areas on the Brazilian coast, especially in the last 50 years. Despite the existence of a strict and dynamic environmental legislation, it is still poorly enforced, accumulating environmental liabilities that today are a challenge for the management of coastal areas. The methodology employed in this paper is expected to be useful for identifying other rivers suppressed by urban occupation, as well as for analyzing environmental liabilities in order to require environmental recovery and compensation measures that effectively correlate with the area subject to environmental damage.

The incorporation, in coastal management, of methods for analyzing the environmental degradation of protected areas by urban occupations,

Table 1
Faustino and Meio rivers beds and respective PPA suppressed considering each occupation period and the environmental limitations defined by the environmental legislation in force in each period. Specially protected overlapping territorial spaces have already been considered. Values in hectares (ha).

OCCUPANCY PERIOD	DAMAGED RIVER BED	LAW IN FORCE		
		Law 4771, 1965 in original wording	Law 7511, 1986	Law 7803, 1989 succeeded by Law 12651, 2012
Prior to July 7, 1986	19.70	25.65	62.82	61.44
July 8, 1986 to July 19, 1989	0.00	0.00	0.00	0.00
After July 20, 1989	8.32	9.76	28.00	26.55
TOTAL	**28.02**	**35.41**	**90.82**	**87.99**

integrated with the procedures for land regularization, can provide a unique opportunity for urban intervention to create areas that, in addition to ecosystem functions, add features that assist in adapting and mitigating the effect of climate change on low-lying coastal plains, as well as providing better quality of life for people. For future work we suggest the development of similar methodologies for other PPA modalities and incorporate procedures to quantify the environmental damage due to interim loss of natural resource (cf. Scemama and Levrel, 2015; Desvousges et al., 2018; Lipton et al., 2018).

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. Supplementary data

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