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REVIEW

Data rescue process in the context of sea level reconstructions: An overview of the methodology, lessons learned, up-to-date best practices and recommendations

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Abstract

Coastal water level measurements represent one of the earliest geophysical measurements and allow an assessment of historical sea level rise and trends in tides, river flow and storm surge. However, recovery and digitization of archival tidal records have been much less widespread and systematic than, for example meteorological records. In this contribution, we discuss data rescue efforts and lessons learned in France, the United States and the United Kingdom, countries with early and extensive tide gauge networks by the mid-19th century. We highlight the importance of (a) cataloguing the historical gauge records, as a first step towards locating them; (b) locating data in archives, and then recovering and saving data by any means necessary, including photographs and scanning; (c) obtaining metadata, including both quantitative survey records, gauge checks and clock data, but also qualitative records such as gauge notes, letters and reports; and (d) quantitative statistical analysis of data and datum quality, using both standard data-entry checks but also tools that leverage the unique predictability of tide measurements. Methods for digitizing original analogue records are also discussed, including semi-automatic, computer-based methods of digitizing tidal charts (marigrams). Although the current best practice is described, future improvements are desirable and needed to make the more than estimated 10,000 station years of unused, undigitized records available to the scientific community.

KEYWORDS

data rescue, oceanography, sea level

1 | INTRODUCTION

1.1 | Why this review?

In March 2020, the first Workshop on Sea Level Data Archaeology was held (Intergovernmental Oceanographic Commission/UNESCO, 2020). The main objective of this international meeting was to bring together experts active in data rescue activities to explore the potential for a more sustained programmatic approach to cooperation at the international level. The importance of observations has been underscored in the context of the ocean decade, the resolution passed by the United Nations General Assembly in 2017 to focus on sustainable development and ocean science during the 2021–2030 decade (Heymans et al., 2020). Thus, modern measurements including real-time ones are needed 'to develop scientific knowledge, build infrastructure and foster relationships for a sustainable and healthy ocean'; however, historical measurements are also needed to understand modern ones in a long-term context. Data rescue projects are still rare and can be limited due to multiple challenges (limits to resources, finding data, capturing original data, etc.) and the workshop provided a much-needed forum to present the detailed methodology, lessons learned and up-to-date best practice standards applied in these projects. In this paper, the work of sea level data rescue in these various aspects is presented (archive centres, investigation, inventory, scanning, digitization tools, archiving, valorization, etc.). An attempt was made to give many examples from different countries, in order to better illustrate the methodology and to give the most exhaustive overview of this topic as possible.

1.2 | Definition of data rescue?

The Global Oceanographic Data Archaeology and Rescue (GODAR) project defines 'data archaeology' as the process of seeking out, restoring, evaluating, correcting and interpreting historical datasets, and 'data rescue' as the effort to save data at risk by digitizing manuscript data, copying to electronic media, and archiving these data into an internationally available electronic database (Caldwell, 2012; Levitus, 2012). Historical data are usually interpreted as data that is at least several decades old and precedes modern digital databases. The term 'data archaeology' has roots in the computer science field, and refers to recovering the data encoded in now obsolete media or formats like tapes or 5.25″ floppy disks (Levitus, 2012). This term is now also widely understood as the data mining and rescue of pre-digital datasets, and used in the science of sea level where digging into the past for long-term sea level time series covering many decades is an important way to better understand climate change (Hogarth, 2014).

1.3 | Why is data archaeology important for sea level science?

The study of global long-term sea level variability is a subject of major importance, due to its association with climate change and its direct societal impact (IPCC, 2013; Oppenheimer et al., 2019). Enormous efforts have been undertaken to better understand the mechanisms that drive such variability, and numerous works highlight the complexity of the response both over temporal and geographical scales. Even though satellite altimetry has proven to be a very powerful observation tool to derive a global overview of sea level variability, altimetry data with sufficient spatial and temporal coverage have only been collected for the last three decades. Thus, one of the issues typically raised by sea level scientists is the scarcity of sea level time series which span the past century and longer. This demand illustrates the importance of sea level data archaeology to better constrain the rate of Global Sea Level Rise (GSLR) and its possible acceleration (Jevrejeva et al., 2017), but this exercise is not restricted only to long-term data series (records over more than several decades) and can also include shorter records (Hunter et al., 2003; Testut et al., 2010; Woodworth et al., 2010).

In this context, the International Hydrographic Organization (IHO, since 1921) coordinates the activities of Intergovernmental hydrographic offices and promotes uniformity in nautical charts and documents. In terms of data measurement, the IHO Tide Water Level and Currents working group focuses on providing guidelines to maximize the use of hydrographic survey data. Past publications of the IHO have published lists of tidal archives and are a good resources for beginning to catalogue historical records (e.g. IHR (International Hydrographic Review, 1932)).

Data archaeology science is partially made of ad hoc studies due to scarcity of these data and is time consuming and therefore costly. Sharing the data rescue knowledge is therefore beneficial to science. To recover records and ensure consistent time series, one must address data completeness and continuity issue, vertical referencing and data uncertainty (IHO-TWCWG, 2010, 2016). Consequently, the scope of data rescue should include information on methods, uncertainty control, time measurements and the vertical datum.

Long-term datasets help refine understanding of sea level rise and trends in tides (Haigh et al., 2020). Historical water level data can also refine estimates of flood hazard, by providing a larger density of measurements in the tails of distributions (Talke et al., 2018). Moreover, estimates of sea level rise also inform studies of vertical land motion (Spada & Galassi, 2012). This is partly why detailed historical data stored in a collective database have a direct positive impact for research in several disciplines, including climate science, marine submersion (Goutx et al., 2014), geology and understanding of oceanic variability.

1.4 | A short history of sea level measurement

For centuries, sea level variability has been measured by many nations in order to address specific needs. Over historical times, technical progress improved sea level observations. An example of this historical evolution can be illustrated through the French experience, where sea level observations were already made at the end of the 17th century. In order to update the map of France by knowing the value of the meridian, the astronomers de La Hire and Picard carried out the first systematic sea level measurements at Brest and Nantes (Picard & de La Hire, 1729). Supported by the French Royal Academy of Sciences, tidal measurements became widespread in the 18th century. At these times, water level measurements were made by a direct reading on a graduated tide staff. Until the middle of the 19th century, sea level measurements were made by astronomers in order to establish a general scientific theory of tidal phenomena and thus, to develop a method for predicting the tide. At the end of the 1830s, the *Dépôt des cartes et plans de la Marine*, the forerunner of the French Hydrographic Service (nowadays Shom), generalized water level measurements by deploying the first tide gauge network on the French coasts and later on its overseas territories. The objectives of this network were to meet hydrographic needs (datum definition) and to use sea level measurements to predict tides and construct tide tables. The development of a self-registering float tide gauge with stilling wells in the mid-19th century was a major technological improvement in water level measurements (Woodworth, 2021). Improvements continued in the 20th century with pressure and later radar tide gauge technology.

The development of tidal science and tidal measurements in the United Kingdom, following an arc from individual practitioner to government supported science, is described in Reidy (2009). In the early 19th century, W. Whewell and J. W. Luddock initiated a worldwide collaborative research project to study tides between maritime states leading to simultaneous observations around the American and the European coastlines (Reidy, 2008; Yeo, 2003). The development of the US Coast Survey (which became the US Coast and Geodetic Survey and was later incorporated into the National Oceanographic and Atmospheric Administration, NOAA) is discussed in Manning (1988) and Slotten (1994). In particular, Manning (1988) discusses the political battles fought over the high-quality (but expensive) data produced by the civilian Coast Survey during the 19th century, vs. the inexpensive but less scientifically rigorous approaches of the Navy Hydrographic Office. Fortunately, the high-quality, publicly available data produced by the US Coast Survey prevailed over the measurements of the Navy that had more restricted public access. The US tradition of making many geophysical measurements available to the public, begun by the US Coast Survey, continues in the United States to this day. For some national tidal agencies, there may still be restrictions in regard to data exchange due to possible national security or cost recovery policies, and in some cases, it may be a reason that tidal records are not as well preserved or available as meteorological records (Brönnimann et al., 2019). However, available documentation from the IHR (International Hydrographic Review, 1932) shows that at least 13 countries (not including the United Kingdom) had extensive tidal networks by the early 1900s, both at home and in overseas territories (see also Talke & Jay, 2013).

1.5 | Present-day situation (the GLOSS program)

In the 20th century, after some decades during which the interest in sea level observations declined (Pouvreau, 2008), there was a renewed concern after the International Geophysical Year (July 1957–1958) which resulted in many new tide stations being set up around the world. At the end of the 1980s, new societal challenges and the needs of in situ validation for the emerging sea level monitoring systems based on satellite altimetry and global circulation models resulted in a densification of the tide gauge network in the world. For this purpose, the UNESCO Intergovernmental Oceanographic Commission (IOC) created the Global Sea Level Observing System (GLOSS) in 1985. GLOSS is an international sea level monitoring program designed to produce high-quality in situ sea level observations to support a broad research and operational user base. This program is currently formed by over 90 nations across the globe to provide oversight and coordination for global and regional sea level networks and relies on feedback and direction from local tide gauge operators to maintain the creation of high-quality sea level observations. Thanks to this program several global data centres collect, archive and freely distribute sea level observation to the users (Levitus, 2012); an example is the University of Hawaii Sea Level Center (UHSLC) (Caldwell, 2012). These data centres receive newly acquired observations year after year. Moreover, individual agencies such as NOAA or Shom, and collaborative programs such as the World Ocean Circulation Experiment in the 1990s, have worked at various times to digitize and/or make available historical records (Caldwell, 2012). However, there are still sites, at which measurements have been made as early as the 18th century, where the observations have not yet been integrated in the international data banks.

1.6 | Sea level time series reconstruction

One of the goals of many sea level data archaeology exercises is to study the long-term evolution of Mean Sea Level (MSL). To our knowledge, the first published example of data archaeology applied to sea level science was the recovery of historical high water at Liverpool since 1768 (Woodworth, 1999). Since then, a few authors have spent time digging into their national archive in order to extend back into the past already existing sea level time series. These include Brest (Pouvreau, 2008; Wöppelmann et al., 2006, 2008), Marseille (Wöppelmann et al., 2014), Dunkirk (Latapy, 2020) and Saint-Nazaire (Ferret, 2016) in France, Cadiz (Marcos et al., 2011), Tenerife (Marcos et al., 2013), Santander and Alicante (Marcos et al., 2021) in Spain, Leixões (Araújo et al., 2013) in Portugal, a few sites within the British Isles (Hogarth et al., 2020), and Boston and Astoria in the United States (Talke et al., 2018; Talke, Mahedy, et al., 2020). It is also remarkable that sea level data archaeology allowed us to discover new information on long-term mean sea level evolution in the Southern Hemisphere, where very few long time series exist (Hunter et al., 2003; Testut et al., 2006, 2010; Watson, 2017; Woodworth, 2005; Woodworth et al., 2010, 2012).

1.7 | Analysis of historical records

The extension into the past of existing time series or the (re)discovery of new time series enables multiple types of oceanographic analysis. Historical sea level records can help constrain rates of changing sea levels and identify regions with local variability (Church & White, 2011; Hay et al., 2015; Hogarth, 2014; Jevrejeva et al., 2008; Talke et al., 2018; Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). Extended datasets can also be used to identify intra-annual to decadal sea level variability (Dangendorf et al., 2013).

Tidal measurements are often the longest, and only measurements that are available for evaluating long-term changes in coastal and estuarine regions, and discerning their cause (Talke & Jay, 2013, 2020). Extended datasets have enabled assessment of changes in the nontidal residual and/or storm surges (Bromirski et al., 2003; Haigh et al., 2010; Talke et al., 2014). Moreover, quantitative measurements of water levels during storms can become the basis for retrospective/reanalysis storm models (Haigh et al., 2010; Harker et al., 2019; Marcos & Woodworth, 2017; McInnes et al., 2016; Talke et al., 2014; Woodworth et al., 2011).

Anthropogenic coastal changes or changes in oceanic circulation and stratification can affect tidal characteristics (tidal range, harmonic components, tidal asymmetry, etc.; Church & White, 2011; Familkhalili & Talke, 2016; Gouriou, 2012; Haigh et al., 2020; Jay, 2009; Li et al., 2021; Pineau-Guillou et al., 2021; Ray, 2006; Ray & Talke, 2019; Talke et al., 2018; Talke, Familkhalili, et al., 2020; Talke & Jay, 2020; Talke, Mahedy, et al., 2020; Woodworth, 2010). For sites on tidal rivers, historical tide gauges can also help quantify historical river floods and flow statistics (Moftakhari et al., 2013, 2015, 2016; Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). The aim of this paper is not to describe all the possible scientific applications of long-term sea level time series. The reader interested in seeing the possible use of such long-term records are encouraged to read the online report written by Talke and Jay (2017) which gives some of the possible applications and uses of historical water level measurements with examples for some sites around the world.

The format of the paper is as follows; Section 2 presents the archival investigation leading to the most exhaustive and complete inventory possible. In this section, the inventory process is detailed with a particular attempt on the inventory diffusion. The documents sought in the context of reconstructions are also listed. Section 3 outlines the data rescue process, from the initial paper document, to the extraction of the data with the digitization of the tidal signal. Correction and validation steps of the extended dataset are described in Section 4. In Section 5, we briefly discuss the integration of recovered sea level datasets in existing data repositories to make them available to the community. Finally, we outline some future directions and conclusions in Section 6.

2 | ARCHIVAL RESEARCH – INVENTORY

Data archaeology is often started by producing an inventory of historical measurements. This helps guide the search in archives, and, in the best case, results in a new sea level time series. We will describe in this section the type of resources usually encountered in archived.

2.1 | The inventory process

Archival documents can be classified into two main categories: (a) the data, that is the measurement itself and (b) the metadata, that is all the associated documents that put the data into context. Sea level measurements were performed by different people and institutions over the time in order to fulfil different purposes. Consequently, archives related to these observations are scattered in different locations, and it is usually not an easy task to track them.

The first very important step in data archaeology is to inventory the documents related to sea level measurements (Talke & Jay, 2017). This inventory, as exhaustive as possible, aims at identifying historical archives, often preserved only in paper format, in order to be aware of their existence and then rescue them. These documents can be stored in dedicated locations that are supposed to be ideal for document preservation, including national archives and national organizations that provide hydrographic services. Data are also often stored in other locations including regional and local government offices, research institutes, port authorities, personal archives of individual scientists and engineers, naval military archives, national and local libraries, and other locations. Many such locations often include non-ideal storage conditions and are at risk at being lost and destroyed (Caldwell, 2012). Although it is reasonable to think that a large amount of tidal data may have been lost or destroyed over time, a significant number of documents remain and have been kept in archives centres (see Talke & Jay, 2013, 2017).

Consequently, the initial action is to identify where records are stored, for what stations and dates, on which type of media, and in what condition in terms of readability. Depending on the institutions storing the data, the existing inventory may not be totally complete or sufficiently accurate. It is often necessary to visit on-site to examine each document and determine whether or not the data can be rescued and used.

In France, a national inventory was produced as part of Nicolas Pouvreau's PhD (http://refmar.shom.fr/). This effort inventoried the quantity and quality of recordings available in mainland France as well as in French overseas territories. Hogarth (2014) extended the Permanent Service for Mean Sea Level (PSMSL) tide gauge data base using historical information dating back to the 1800s, adding a substantial archive of approximately 4,800 station years of monthly data, including many non-standardized observations that were already public. In the USA, more than 6,500 station years of previously 'lost' or forgotten tide data have been identified as part of the work of North America data rescue (Talke & Jay, 2013, 2017). However, only 1/4 of the numbers of documents inventoried were recovered to date (Talke & Jay, 2017). Unlike meteorological records, which have recently been the subject of an international inventory (Brönnimann et al., 2019), national inventory efforts of tidal data are very limited and have been done mostly in the United States and the United Kingdom. In France, Shom has made available online its inventory of historical tidal data (http://refmar.shom.fr/dataRescue/).

The notion of inventory is more complex than it seems. In fact, the reconstruction process requires identifying not only the data but also the metadata associated with the measurement. In the following sections, the different types of data and metadata sought are presented and detailed. The difficulty of the exercise lies in the fact that we are looking for both quantitative and qualitative data. As much as listing measurements may seem easy (it is enough to indicate the site, the period of measurement, the type of measurement and the format), the inventory is not so simple as far as metadata are concerned.

The inventory phase is certainly the first step to be taken in reconstruction projects, but it is also an essential phase that makes it possible to assess the availability and potential of existing measurements.

2.2 | Data and metadata

Tidal records can have very different origins, and serve many purposes (Talke & Jay, 2013). A non-exhaustive list of such sources includes observations from fixed gauges; data from temporary tide staffs used in hydrographic surveys; tide gauges used for military purposes; short-term campaigns from civil engineering, scientific and harbour surveys; and long, fixed measurements used for tidal predictions and definition of tidal datums.

2.2.1 | Sea level measurements

Water level records can be found either in the form of handwritten ledgers or marigrams.

Tidal ledgers are in the form of large paper sheets (bound or not) containing tables of sea level measurement. Ledgers can include daily, monthly or yearly mean sea levels. High-frequency measurements can also be found in the form of handwritten ledgers (every 15 min or sub-hourly, hourly records, see Figure 1a,d) as they can concern only the height and the time of the high and low (HL) tides according to the observatory's purpose (Figure 1b,e;

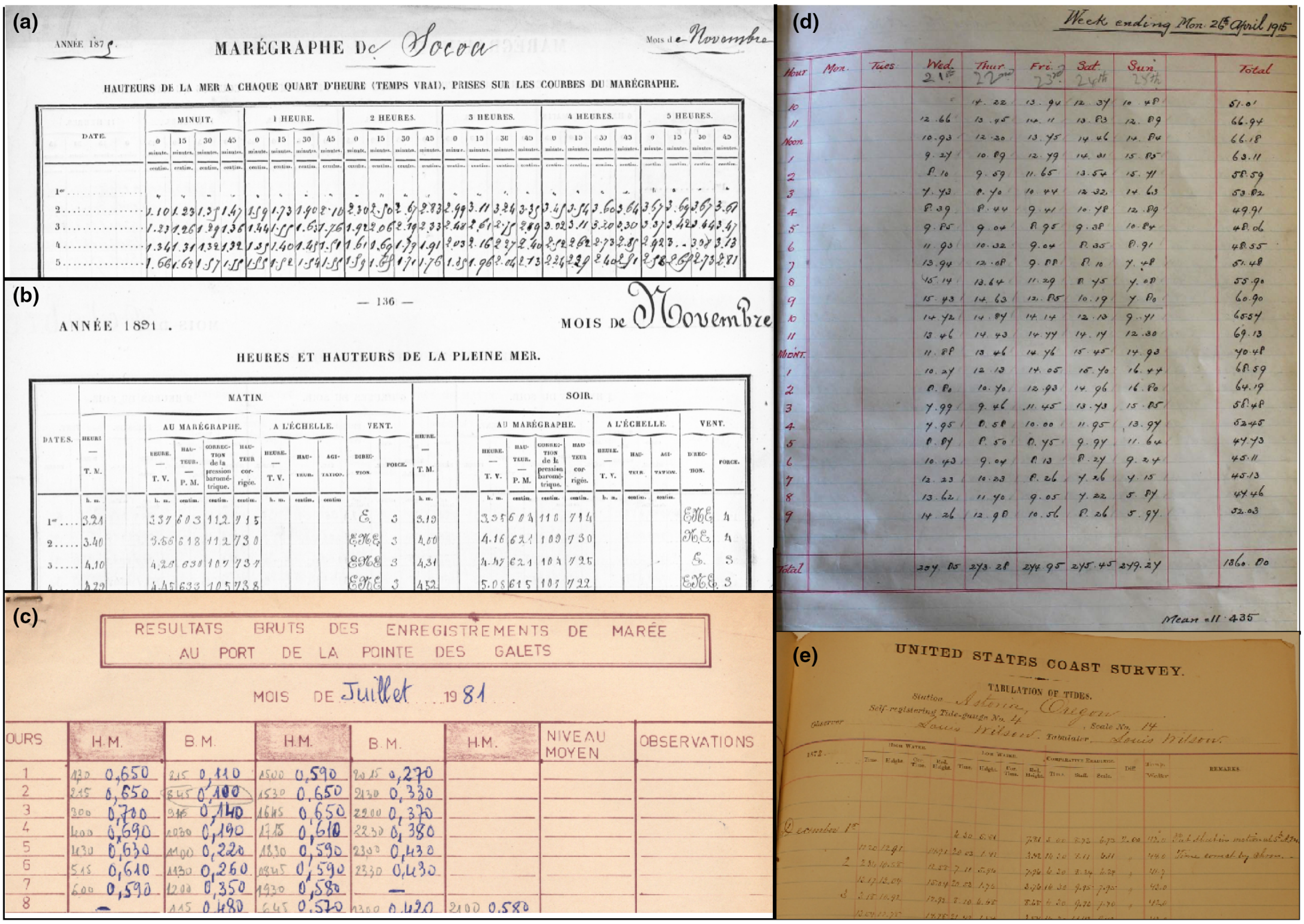

FIGURE 1 Example of tidal ledgers for some tidal observatories: (a) High-frequency measurements made in Socoa in 1875 (15 min-frequency) (source: SHD Rochefort); (b) Time and heights of high tides reported for Rochefort in 1891 (source: SHD Rochefort); (c) Time and heights of high and low tides reported for la pointe des Galets in 1981 (sources: Shom); (d) Example of hourly sea level measurements made at Newlyn, UK in 1915 (from Bradshaw et al. (2015); (e) Example of high/low data and staff/tide gauge comparisons, from December 1872 at Astoria (OR/USA) (source: National Oceanographic and atmospheric administration [NOAA] headquarters, silver spring, Maryland. Photo credit: Stefan Talke)

or only high water (HW) heights as for Brest and Liverpool during the 18th century). Most of the oldest measurements are kept in this form. Historically, this was the most common form used for investigating and studying the tide phenomenon. Initially, the first measurements were made by an observer who read directly on a tide staff the water level at a given time. In addition, high water and (sometimes) low water were the only measurement most scientists and engineers were interested in: there was little appreciation of the value of the full tidal curve until the harmonic method was developed (with a few exceptions, such as for Bristol, in November 1,668, where sea levels were reported every 15 min for tidal research in the Philosophical Transactions). In fact, even after the introduction of mechanical tide gauges for some sites, marigrams (see further below) were regularly scrutinized and water heights (or HL water heights only) were transcribed on ledgers. Extremal measurements (HL waters heights) are often still preserved in ledgers (Figure 1c). One such example is Saint-Malo (France), where the high tides were reported daily by the harbour master's office between 1946 and 1982.

Considering marigrams (also called mareograms, mareographs, and tidal charts), they are the continuous graphical curve of the sea level variation recorded by a float tide gauge on a paper sheet installed on rotating drums. These graphical documents usually represent a continuous analogue measurement of the water level (Figure 2). A stilling well usually filtered out wave motions, giving an approximate time resolution on the order of minutes. Please refer to Pugh and Woodworth (2014) for more information on float gauges, and Talke, Mahedy, et al. (2020) for estimates of historical accuracy. Marigrams can also correspond to daily averages obtained from a device that enabled the mechanical integration of the float gauge recordings into an averaged value, as was done in Marseille (Coulomb, 2014;

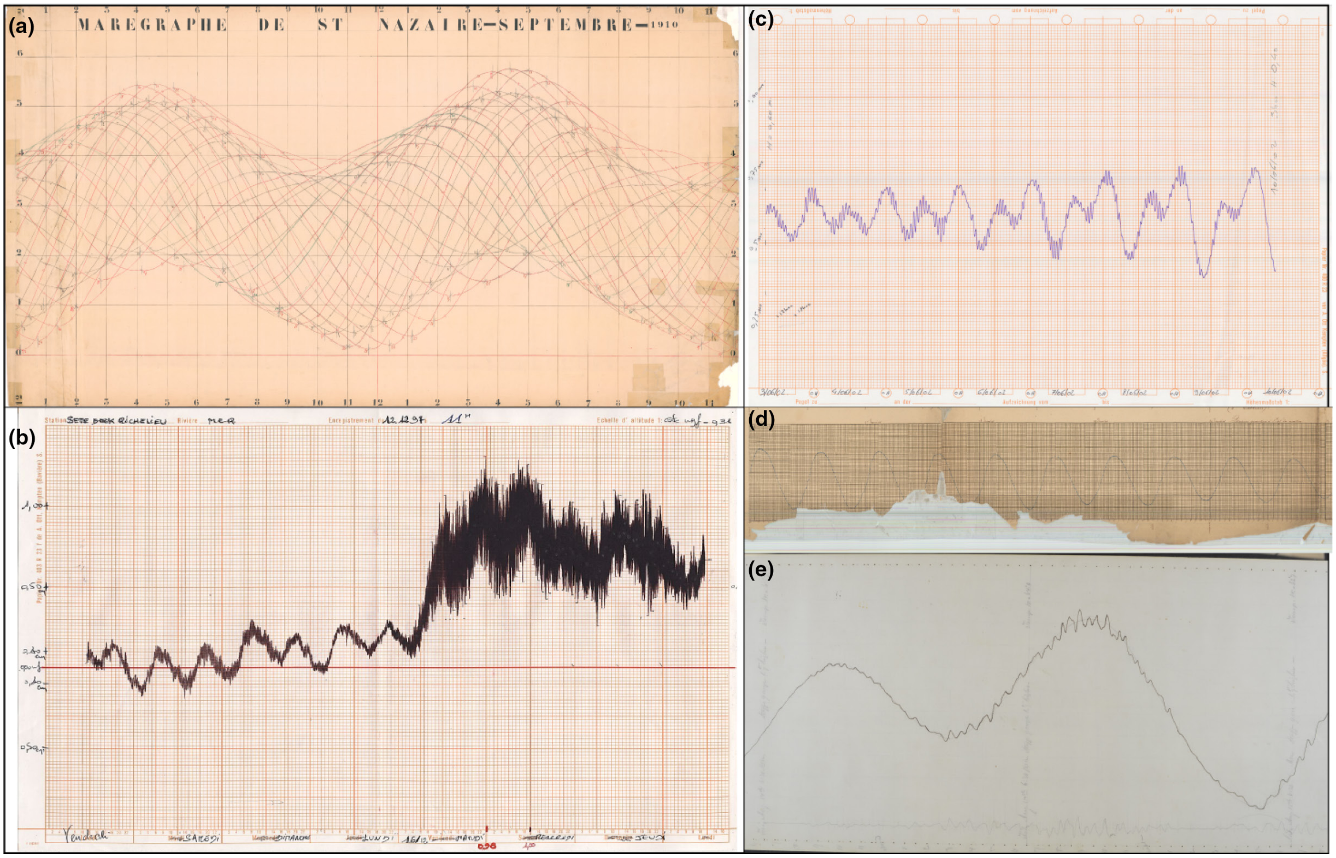

FIGURE 2 Example of several forms of marigrams: With multiple curves over a month at Saint-Nazaire (Atlantic Sea) (a), with a single curve per marigram over a week at a microtidal mixed semidiurnal site in the Mediterranean Sea (Sète) recording a storm surge in December 1997 (source: Cerema/DREAL Occitanie) (b) or at another microtidal mixed semidiurnal site in the Caribbean Sea (pointe à Pitre) (c) (sources: Shom); zoom on a marigram recorded in Dunkirk (North Sea) in 1865 over a month with significant holes and folds (source: Shom) (d) and example of a tsunami caused by the August 13th, 1868 Arica (Chile) earthquake, captured on the marigram roll at Astoria (OR) on August 15th (source: US National Archives in Kansas City. Photo credit: Stefan Talke) (e)

Wöppelmann et al., 2014), in Cadiz (Marcos et al., 2011) and in Helgoland (Rohde, 1982).

Marigrams can be of several types: either a single curve per marigram or multiple curves per marigram. The first type is very common in the USA, the UK, on the French Mediterranean coast and other locations. In the microtidal regime, the tidal range amplitude (<50 cm) does not allow to distinguish curves from 1 day to another if the daily curves are superimposed. In these cases, single curve per marigram records are preferred (Figure 2b,c). Sometimes, single curve per marigrams may be found for semidiurnal coasts; the water heights were reproduced in the form of marigrams and can be in the form of long sheets with 1 month of measurement as it is the case in Dunkirk between 1865 and 1875 (Figure 2d).

The second type of marigram is quite common in semidiurnal coasts with a high tidal range due to major semidiurnal components (with a periodicity of approximately 12 hr 25): every 24 hr, times of high and low waters are shifted by about 50 min, allowing one to distinguish one daily curve from another (Figure 2a). In the case of the Atlantic and the English Channel coasts, variations in tidal range amplitude and timing enable each curve to be identified, if the measurement duration is less than 2 weeks. However, in our experience, tide sheets were not always changed as regularly by the observer. In these cases, multiple curves accumulate on the paper and overlap, resulting in recordings of several weeks to a month per tide sheet that are more challenging to interpret.

The introduction of the marigrams made it possible to have the continuous tidal signal and thus to record the high-frequency signals. Many charts show evidence for high-frequency variations in sea level due to seiches or even tsunamis (or meteotsunamis; Figure 2b,e). For instance, many marigrams from Scotland or La Réunion have seiches (see Figure 7d).

2.2.2 | Metadata

Metadata corresponds to additional measurements such as auxiliary staff measurements, time checks, levelling

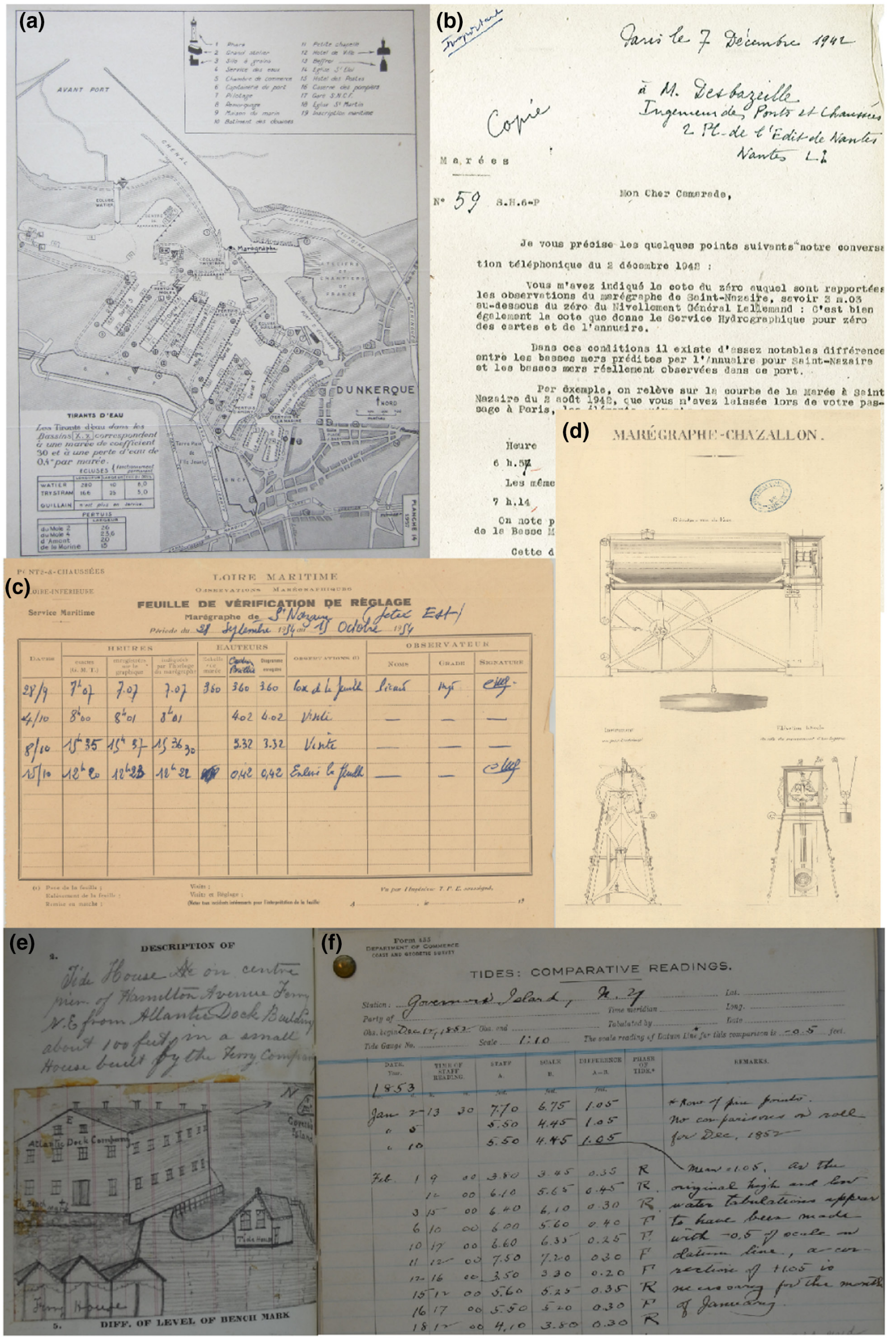

FIGURE 3 Different type of ancillary documents: (a) plan of the location of the tide gauge in Dunkirk (source IGN, boite 1,346); (b) letter reporting the levelling between the St-Nazaire tide gauge datum and the geodetic network of the time in 1942 ('Nivellement Général Lallemand'; source: Shom); (c) control sheets of the Saint-Nazaire tide gauge in 1954 (source: Grand port maritime de Nantes Saint-Nazaire); (d) 'Chazallon tide gauge' plan (source: Shom); (e) Drawing of the location of the new tide house of Brooklyn made the 27th august 1861 (source: Record group 23 [hydrographic records of the US coast and geodetic survey] in the US National Archive at College Park, Maryland. Photo credit: Patrick Lau); (f) Comparison between automatic tide gauge heights and those read on the scale at the Governor Island station in 1853 (source: Record group 23 [US coast and geodetic survey], in the US National Archive at College Park, Maryland. Photo credit: Stefan Talke/Patrick Lau)

surveys, meteorological observations, qualitative notes, letters or any additional documents that may subsequently help to put the water level measurement into context (Figure 3). Examples include the site location (Figure 3a), tide house position (Figure 3e), vertical attachment (Figure 3b), equipment changes and other information. When the observatory was set up, the zero of the measurement was defined, measurement conventions were taken, calibration procedures were also established. All these information and conventions constitute the metadata. Depending on the type of information sought, it will be necessary to create several varieties of documents (the same document may sometimes fill in several fields). A non-exhaustive list is presented in Table 1.

As outlined by Talke and Jay (2017), contemporaneous notes and letters provide a chronology of each device and can help identify particularly problematic periods caused, for example by gauge malfunction, change in observer, dock subsidence, sedimentation or clogging of the intake holes in the stilling well. Documents should therefore be sought about the types and models of the tide gauges (Figure 3d), the recording mechanisms, clocks, time- and vertical-data reduction, calibration, geodetic levelling, measurement of additional environmental parameters at

TABLE 1 Example of documents providing contextual information on the water level measurements recorded with float tide gauge (similar situation applies to pressure gauges – the density and gravity must be known – and to radar gauges for which the zero needs to be calibrated)

Information provided	Type of document/notes
Type of devices used	• Plans • Contemporary letters • Photographs
Datum	• Levelling/survey reports • Photographs • Drawings • Calibration notes during the installation of the device • Description of the measurement procedure • Letters between different organizations • Routine elevation checks • Historical maps indicating the observatory position • Letters indicating settling of the dock • Official levelling networks • Notes written in the margin on the ledger or on the marigram itself
Time	• Letters reporting device used • Letters indicating clock dysfunctioning • Device technical instruction (time data reduction) • Calibration notes during the installation of the device • Routine time checks • Notes written in the margin on the ledger or on the marigram itself
Data quality	• Letters/documents reporting siltation issues • Dredging reports • Newspaper articles (storms identification) • Comments on the measurements noted in the margin on the ledger or on the marigram itself • Letters indicating change in observer • Dipping well measurements (Van de Castille tests)
Additional measurements	• Meteorological measurements, including atmospheric pressure, air temperature, rainfall, cloud cover and wind velocity • Water temperature • River stage and river flow

the tide station and the availability of technical, maintenance and processing notes.

For example, for float tide gauges, during the change in the sheets on the recording drum, routine time and elevation checks could take place (Figure 3c,f). The observer would read the water level and the time indicated on the marigram and compare it with the height read on a tidal staff nearby and the time on his watch. From these control sheets (Figure 3c), it is possible to correct any temporal or vertical drifts or shifts.

It is also important to learn whether the historical benchmarks can be linked to the existing geodetic network for a given station. Indeed, over time, the types of measurements and devices have evolved. Nevertheless, in order to connect all these different sets of measurements together, it is necessary to have common levelling benchmarks; otherwise, the measurements cannot be connected to each other. The difficulty with historical data lies in the possible loss of the levelling documents and the destruction of the geodetic markers over time. Obtaining meta-data is time consuming but helps identify such reference shifts, explain missing data and generally improve the confidence level in the data.

3 | THE DATA RESCUE PROCESS

In the data rescue exercise, data must first be preserved and then made available for scientific researchers. The first step involves the recording of the paper document, and the second step the extraction of the signal (digitization).

3.1 | Media recording

As presented in Section 2, there is a wide variety of paper data types (ledgers, marigrams, etc.). Usually, during the inventory phase, if conservation conditions have not been optimal, there is a risk that some documents may have deteriorated over time and the sea level information they contained may be lost. In this context, it is essential to preserve and save the information. The most perennial solution that has been found is to dematerialize these documents either by photographing them (see Section 3.1.1.) or scanning them (see Section 3.1.2.) for redundancy and/or to prevent further data loss. This process must be done with extreme care because of the risk of document damage or destruction.

Nevertheless, even after this step, the question of preservation can still arise. Indeed, if the digitized documents are kept on a single hard disk, the risk of loss is just as high. Moreover, it remains an open question whether present-day preservation formats (digital image or pdf) will be readable in the future; certainly, many records kept on punch cards, floppy disks, tape drives and even compact disks are becoming unreadable, due to lack of machine readers or due to data deterioration. Knowing this, the sea level data archaeology workshop held by UNESCO (Intergovernmental Oceanographic Commission/UNESCO, 2020) stressed the importance of preservation of original records (usually paper) through appropriate archive arrangements and to avoid dispensing records when they have been data rescued.

3.1.1 | Photography

One way to dematerialize documents is to take photographs of the documents at the same time as they are inventoried (Talke & Jay, 2017). For documents that are really fragile and not stored in appropriate conditions, taking pictures allows scientists to save and preserve these data. On this purpose, different approaches can be applied, including

1. ‘Better than nothing’ mode: pictures are taken with a simple camera, regardless of image distortion caused by the lens or the angle of the photograph. The method is fast, portable, flexible, can be done with any equipment and enables the digital preservation of information. Some modifications are possible; for example, a camera mounted to a tripod and operated with remote triggering can reduce jiggle and image smearing (Talke & Jay, 2017). For tabulated data that will be digitized by people, the ‘better than nothing’ mode is generally sufficient. However, such simple pictures are not necessarily consistent with good practices in the archival community (distortion and resolution) and may not work well with optical character recognition or other automated ways of reading data. Instead, this can be considered an expedient method that allows the preservation of an exploitable trace of the data, just in case.
2. According to archival standards: To stabilize photo shoots, the camera is mounted on a camera stand. An overlap of ~50% with each previous image is used in order to minimize data loss. A high-quality, low distortion lens is used, and a manufacture-based algorithm to reduce issues such as barrel distortion is applied. A known background grid is photographed and used to correct any residual image distortion in post-processing (Talke & Jay, 2020).

For very fragile documents, really damaged by the passage of time (Figure 2d), it is sometimes difficult or even impossible to dematerialize them other than by photographing them without restoring or consolidating them first.

3.1.2 | Scanning

The scanning of documents is another viable preservation method and potentially produces more consistent and reproducible images than taking pictures. However, some archives do not allow the scanning of marigrams, due to the potential for damaging the fragile paper.

The scanning process is time consuming, costs money and/or needs specific material, but is preferred in order to preserve documents according to archival standards. Most paper documents are likely to deteriorate over time and may no longer be usable in the future. As an example, for some of them, storage has not always been ideal and/or the media used to record the measurements was not really adapted to be time resistant, resulting in fold marks, damaged edges, and holes on the documents, etc. (Figure 2d). In the case of these documents, great attention must be paid to the scanning phase. For some highly damaged documents, a preparation phase is sometimes necessary beforehand to consolidate the document (e.g. border reinforcement).

Documents are scanned with a drum or a flatbed scanner in order to avoid as much as possible image distortion problems that could affect the accuracy of the extracted signal afterwards. It is recommended that an image of a rectilinear grid is scanned along with the documents, to enable later post-processing of residual distortion, as needed.

In France, it is recommended that the digital file from the scanning process is in ‘.tif’ format. The advantage of ’.tif’ format is the simple and therefore fast compression and decompression of such files without loss of quality (Fornaro et al., 2017; Lloret Romero et al., 2008). Indeed, if the compression of these files is necessary, depending on the size of the paper document, it can be done without major data loss with this format and is more easily exploitable in the digitization phase (colour processing, ...).

The objective is to find a compromise between the resolution and the size of the scanned file. Since marigrams sizes are relatively large, the resolutions chosen should be at least 300dpi but it can be adjusted depending on the original document size. For example, very large documents (several metres wide and more than 1 m high; the marigrams described in Talke, Familkhalili, et al. (2020); Talke, Mahedy, et al. (2020) were ~20 m in length) are scanned at resolutions of around 100dpi in order to make it further processable. This type of format complicates not only the scanning process – it is necessary to have the equipment to avoid paper undulations – but also the digitization because the digital file can be quite large and difficult to process.

For the United States of America, Talke and Jay (2017) have referenced more than 300,000 photographs and documents that have been recovered. In France, the Shom identifies more than 60,000 documents: more than half of which have already been scanned. Still, thousands of documents need to be scanned.

3.2 | Digitizing

3.2.1 | Digitizing ledgers

The technology of optical character recognition is not yet used for tidal ledgers, likely because variations in handwriting, formats, record clarity and archival data rescue (see Section 3.1) produce unique digital records that, while interpretable by humans, are not always conducive to scaled up, repeatable digital processing. Sometimes, there may be doubts in reading the records, for example the observer writes 6 which can be confused with 8, or 0 with 9. The digitizer gets used to the writing style, but sometimes, there was more than one person with different handwriting. Therefore, the most common method of recovering data still entails the manual entering of water height values into a computer spreadsheet (Dangendorf et al., 2014; Pouvreau, 2008; Talke, Familkhalili, et al., 2020; Talke & Jay, 2017; Talke, Mahedy, et al., 2020).

A good understanding of the type of document studied is essential in order to define an adapted methodology. Indeed, depending on the type of data to be digitized (continuous measurements or HW/LW), the formalism of the numerical spreadsheet will not be the same.

In order to more easily identify errors that may have been made by the observer, but also input errors, two methods of control are applied in real time to the input data:

1. By the conditional formatting option in the numerical spreadsheet (e.g. Talke & Jay, 2017). Conditional formatting assigns a colour to the data depending on the water height value entered whether it is large or small relative to others. It is easier to visually identify 'anomalous' sea level heights between adjacent values. Colour shades also make it easy to identify high and low water as well as spring-neap cycles (Figure 4a). There is also the possibility to define a spreadsheet with exactly the same design as the original paper. Sometimes, on the original paper, some 'calculations' are available as the average or sum over a day/week/month. It is important to have a direct check of this value to identify potential anomalies.
2. By graphically representing water heights, peaks or outliers that are easily identified (Figure 4b). If recent data are available from the same place as the historical measurements, tidal predictions can be used to check the measurements (assuming that tide has not changed).
3. By creating a link on the spreadsheet to quickly open the original digitized ledger. In this way, digitizer can resolve doubts which can appear during or after quality assurance.

Any attempts to digitize large quantities of handwritten observations are extremely time-consuming and often result in many typographical errors (Le Blancq, 2010). To avoid transcription errors such as repeated or skipped values, entries can be transcribed independently by several users and then compared (Hogarth et al., 2020, 2021). This method was applied, for example to the historical Liverpool tidal and meteorological data (1769–1793) digitization, where every measurement was typed in by people in two countries (Tinkler & Woodworth, 2008). However, resources or people are not always available to carry out this type of exercise.

The GLOSS GE have tried to investigate developments in Handwritten Text Recognition (HTR) technology (Bradshaw et al., 2015). Current projects to improve HTR tend to work with the written word and so require knowledge of sentence structure and word occurrence probabilities to reconstruct sentences, but this machine learning process is long and requires a large database that has not yet been developed. Moreover, the use of artificial intelligence applied to this type of project does not yet give satisfactory results.

In the case of historical sea level measurements spanning decades, the digitization of the tabulated data is a very long process. Obtaining funding to make this reconstruction possible is a challenge because the need and the digitization cost are often not understood by funders. Recently, a new approach has emerged to overcome these

Year	Month	Day	Day n°	00:00	01:00	02:00	03:00	04:00	05:00	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00	21:00	22:00	23:00
1908	2	27	58	296	252	201	157	129	123	137	168	213	258	291	311	312	290	246	195	154	127	124	145	186	240	287	322
1908	2	28	59	340	323	282	223	167	123	105	114	144	197	253	303	337	343	322	274	211	154	122	114	135	184	251	315
1908	2	29	60	368	385	372	326	254	178	119	93	98	138	204	279	341	377	389	357	295	217	144	97	89	120	184	266
1908	3	1	61	343	405	424	403	344	253	161	90	[illegible]	73	123	202	292	396	410	415	373	296	200	117	68	64	108	190
1908	3	2	62	290	378	439	444	425	345	243	135	53	27	53	123	225	324	398	436	425	369	275	166	78	34	45	107
1908	3	3	63	203	317	412	453	453	413	320	200	88	16	2	40	129	237	337	407	433	410	336	224	119	38	5	31
1908	3	4	64	106	219	333	414	451	454	390	284	160	54	-4	0	54	152	262	356	418	425	385	303	190	87	16	0
1908	3	5	65	40	135	245	350	427	453	429	357	249	132	43	-3	16	85	186	290	368	410	404	355	264	162	68	19
1908	3	6	66	18	76	168	271	365	422	433	400	326	224	121	51	30	67	137	230	318	380	396	381	325	242	145	72
1908	3	7	67	40	51	112	200	290	359	395	392	354	284	192	114	63	60	100	170	250	318	359	365	340	290	214	144
1908	3	8	68	92	73	97	152	225	295	343	365	353	315	255	181	123	96	100	144	201	264	311	336	332	309	262	206
1908	3	9	69	153	112	105	130	177	234	284	320	330	319	289	241	187	147	131	144	175	218	265	297	312	311	294	260
1908	3	10	70	219	174	147	142	158	192	234	270	295	305	300	276	242	202	174	160	165	187	221	254	282	296	300	291
1908	3	11	71	270	229	193	170	159	165	185	214	245	272	288	288	277	250	217	188	169	167	179	202	234	260	282	295
1908	3	12	72	294	272	240	203	173	154	150	164	193	228	260	284	294	287	262	228	192	166	159	168	190	225	262	291
1908	3	13	73	313	313	292	257	211	170	141	133	148	182	225	265	294	306	297	266	222	179	145	133	140	170	214	262
1908	3	14	74	300	322	317	290	245	190	142	111	108	133	179	233	281	314	320	303	260	204	152	115	109	129	174	233
1908	3	15	75	292	331	345	332	290	227	165	111	88	98	141	202	265	317	345	338	303	244	177	120	91	95	135	195
1908	3	16	76	268	322	357	357	327	258	191	121	74	64	94	152	226	298	344	355	334	281	202	131	77	66	88	149
1908	3	17	77	227	303	359	378	361	313	234	151	84	51	62	112	192	275	340	375	370	328	252	168	97	58	54	111
1908	3	18	78	192	280	353	393	397	359	291	200	114	58	46	80	152	243	324	379	395	369	303	216	128	70	49	77
1908	3	19	79	146	239	326	388	410	393	336	249	157	80	45	55	113	200	291	364	399	393	345	266	172	92	47	52
1908	3	20	80	102	188	280	357	402	405	368	293	203	114	56	40	76	151	241	324	379	396	366	304	215	127	61	37
1908	3	21	81	64	133	219	305	370	395	380	328	247	154	84	45	51	109	186	274	343	380	379	340	265	180	101	54
1908	3	22	82	55	96	173	257	334	380	388	361	302	221	145	86	70	97	158	239	305	305	384	372	320	247	164	103
1908	3	23	83	73	87	136	215	285	338	371	366	331	272	197	127	89	84	117	175	246	255	348	358	335	290	220	150
1908	3	24	84	103	85	102	156	219	279	324	344	340	305	251	187	135	110	113	147	196	191	306	334	335	315	271	213
1908	3	25	85	156	115	106	122	164	212	261	298	315	309	284	243	190	147	124	124	148	150	240	280	306	312	301	271
1908	3	26	86	228	170	132	117	129	157	198	242	279	300	308	294	262	217	174	146	138	124	181	222	264	296	312	316
1908	3	27	87	294	244	190	145	119	115	133	168	212	256	292	309	305	280	235	184	143	127	128	154	195	245	293	325
1908	3	28	88	336	313	265	205	144	104	88	102	136	191	249	300	327	330	301	247	180	167	98	91	120	170	239	302
1908	3	29	89	352	360	338	283	206	127	72	50	68	112	184	257	320	352	352	317	250	239	93	60	59	100	170	255
1908	3	30	90	333	383	393	362	290	195	103	40	19	44	105	192	280	352	384	375	323	311	138	66	27	38	93	183
1908	3	31	91	278	368	411	416	370	285	170	71	7	-1	35	112	218	313	379	400	379	368	210	105	31	108	31	100
1908	4	1	92	200	313	395	437	432	364	265	171	50	0	2	55	150	256	344	398	409	367	286	178	75	12	0	41
1908	4	2	93	134	245	350	418	441	411	335	225	102	23	-6	15	88	190	290	370	412	399	345	252	140	51	0	8

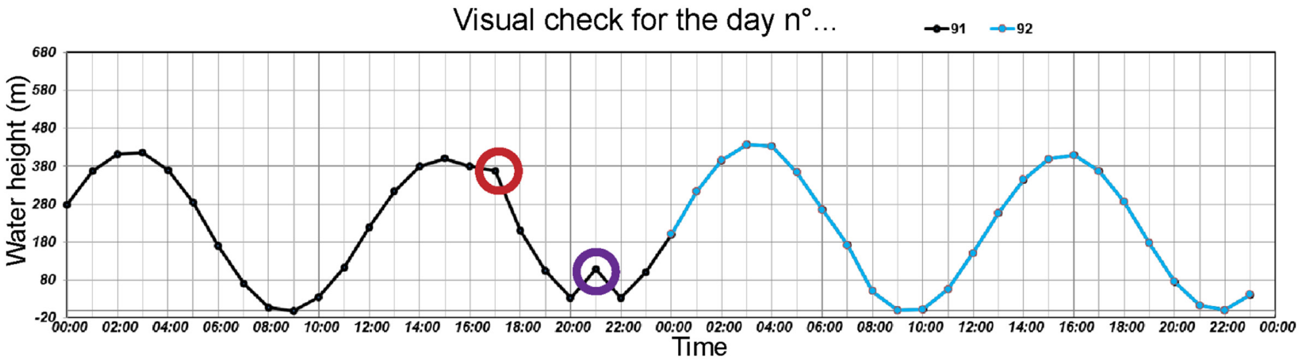

FIGURE 4 Example of numerical spreadsheet used to digitize tidal ledgers recorded in Socoa: Conditional formatting is used to visualize the daily pattern of tides and quickly find and fix outliers and peaks (upper panel); A plot of the data is shown to automatically detect errors (lower panel)

difficulties: citizen science. Projects for historical reconstruction of meteorological data have been pioneering this approach using citizen participation (Hawkins et al., 2019). Using more than 2000 volunteer citizen scientists, Craig and Hawkins (2020) digitized 1.8 million sub-daily and daily weather observations recorded in the UK at the beginning of the 20th century. The advantage of this method is that by using a large number of digitizers, entries can be transcribed independently by several users and then compared. If most of the volunteers agreed on the value, it is accepted; however, if several values are given, the value is checked manually. At the beginning of 2021, one of the first citizen science projects recovering historical tidal data was launched. These ledgers, comprising around 16,000 pages, focus on two locations: Liverpool and Hilbre Island (UK). These projects, which collect a large number of entries, could in the future integrate machine learning to simplify the OCR process on handwritten observations.

3.2.2 | Digitizing marigrams

The other most common form of analogue sea level records are paper charts generated by float tide gauges (see Section 2.2.1.). These recordings transcribe the water height variations on a sheet of paper in the form of daily curves.

In the past, almost all data recovery methods used by hydrographic organizations were manual. Tidal curves were translated into hourly values by hand and eye, or mean values (derived from area under curve) were estimated using a planimeter, a skill now largely lost with the introduction of digitizing tablets in the 1980s. This device usually consists of an electronic tablet and a pen or a stylus. It samples the pen/stylus trajectory at regular time intervals, generating a timestamp and associated water heights. Sea level can also be extracted without any extra equipment, simply by visual reading of the curve and subsampling at the expected time step.

An automatic digitization of the tidal signal is also possible. To extract the digital signal from marigram curves, the software NUNIEAU (NUmérisation des NIveaux d'EAU), developed by CETE Méditerranée (CEREMA, since 2014), is the most commonly used. Another freely available digitization software, Engauge (Mitchell et al., 2020), has been developed to digitize paper charts. Other efforts have developed their own software to deal with unique data formats and conditions; because of their specialized application, these are generally not transferable to other contexts. For instance, Talke, Familkhalili, et al. (2020); Talke, Mahedy, et al. (2020) developed a line-finding algorithm which tracks the pixel coordinates of the pencil trace. Next, the pixel coordinates of known (time, height) points are defined manually by clicking on the image. After correcting for the known barrel distortion of the lens, the pencil trace is scaled into time/height coordinates.

In many cases, curves are not always visible due to paper quality or degradation of the pencil/pen markings. For example, some documents can show significant traces of mould (Figure 5b). The water level recording signal may also have faded partially or completely over time (Figure 5a). In these cases, these scanned documents must undergo an image processing and reconstruction/recovery phase. One strategy is to equalize colour histograms (contrast adjustment), followed by a reduction in the tone, saturation and luminosity (van den Beld et al., 2020). After processing, the curves become visible.

Free portable software such as NUNIEAU enables semi-automatic to automatic extraction of water level data, making them available/analysable in digital format. It is based on a colour recognition algorithm, which allows extraction of the tide signal from the background, when the colours differ. The purpose of the processing is to obtain a temporal series of water levels as clean as possible; it also has vertical and temporal setting tools, and cleaning tools (Pons, 2020; Ullmann et al., 2005).

The extraction of the tidal signal requires several steps (Figure 6):

1. Providing metadata information associated with the water level measurements, such as the starting date of the measurements, the grid characteristics (number and value of unit cells according to x and y) and optional comments;
2. Marigrams are tied temporally and vertically, through the definition of calibration points whose heights and times are known (Figure 6a). This referencing process allows the assignment of real-time/sea level information for each pixel of the image. The software provides several tools to check the quality of this calibration;
3. The definition of the colour to be extracted according to its components of red, green and blue (RGB values) or to the comparison between 2 colours (e.g. blue value greater than red value [Pons, 2020]; Figure 6b). The good definition of these parameters is essential in order not to extract too much, or on the contrary not enough pixels;
4. The image cleaning process during which the areas to keep/exclude during processing are drawn. In the case of a tide gauge with multiple curves, it is during this step that the extraction mask is defined (Figure 6c).

Optimally, the file should be of the order of 50–100 MB in order to be easily processed during the digitization phase. The automatic extraction works very well when only one curve is present on the tidal sheet. In contrast,

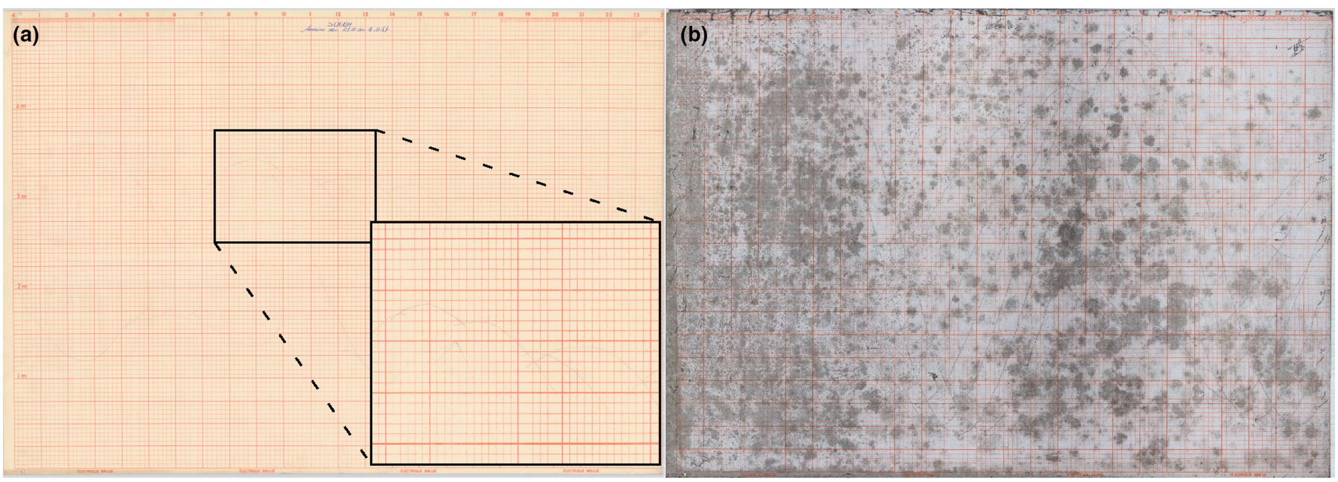

FIGURE 5 Some examples of deteriorated documents: (a) Example of marigram recorded in Socoa in 1957 requiring image processing to accentuate and better visualize the curves (source: Departmental archives of Pyrénées-Atlantiques); (b) Marigram recorded in Socoa in 1963 with several traces of mould around the document (source: Departmental archives of Pyrénées-Atlantiques)

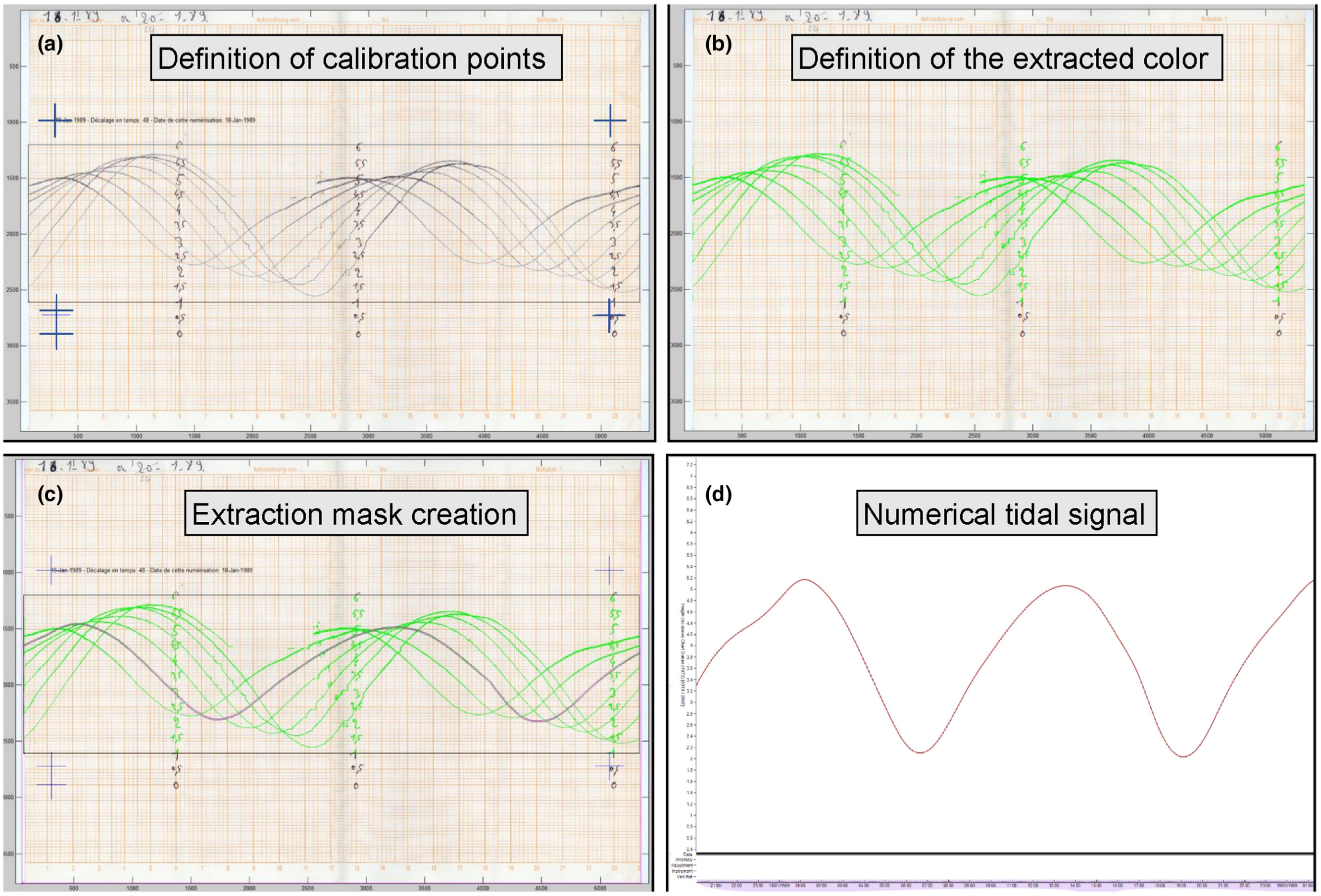

FIGURE 6 Illustration of the steps to follow to digitize a tidal curve with NUNIEAU: (a) Definition of the 5 calibration points; (b) definition of the RGB values to extract; (c) definition of the extraction mask in cases there are multiple curves; (d) final numerical tidal signal

many marigrams are characterized by multiple curves, making the detection more complex. As presented before, on a tidal chart, one or more daily curves can overlap (some marigrams include more than 3 weeks of measurements; Figure 2a). In these cases, it is often necessary to do some post-processing treatments by cleaning the image afterwards. Furthermore, the digitization of documents with a single curve per marigram can also be problematic when more than a month's recordings are kept on rolls more than 10 m long. Once scanned, the numerical image can be very big (>200 MB) and difficult to process with NUNIEAU. This is the case in Bordeaux (France) where measurements were made in 1975 and 1976 on rolls between 11 and 15 m long.

In practice, depending on the quality of the tide charts to be digitized, the semi-automation of the process may be limited. Sometimes, the tide sheets were not changed as regularly as required. In these cases, multiple curves accumulate on the paper and overlap very regularly (Figure 7a,b): It is then delicate, if not impossible, to automatically define 'analysis masks' to distinguish each curve. To overcome this problem, extraction masks can be defined manually, which consists in following the curves on the screen one by one. Once this is done, the signal present inside the extraction mask is recovered and the water heights are estimated according to the time step defined beforehand. The setting up of these extraction masks, curve by curve, day after day, is therefore long, fastidious and repetitive, but it is essential because no other tool currently allows this work to be done more efficiently.

The NUNIEAU software allows extracting curves with regular time steps, minimum, maximum, average values and barycentres which can be useful when the signal is noisy at high or low tides (Figure 7c). For marigrams with noisy signals (Figures 7d and 2b), the curve detection can be more complex. Indeed, multiple intersecting curves can make semi-automatic detection more difficult. It is then necessary, as presented before, to follow the curves one by one manually.

The concept of NUNIEAU is based on a referencing file as the georeferencing process in GIS. There is a link between the native scan image and the refencing file. Thanks to this referencing file, a lot of tools are available in NUNIEAU to optimize human time. NUNIEAU

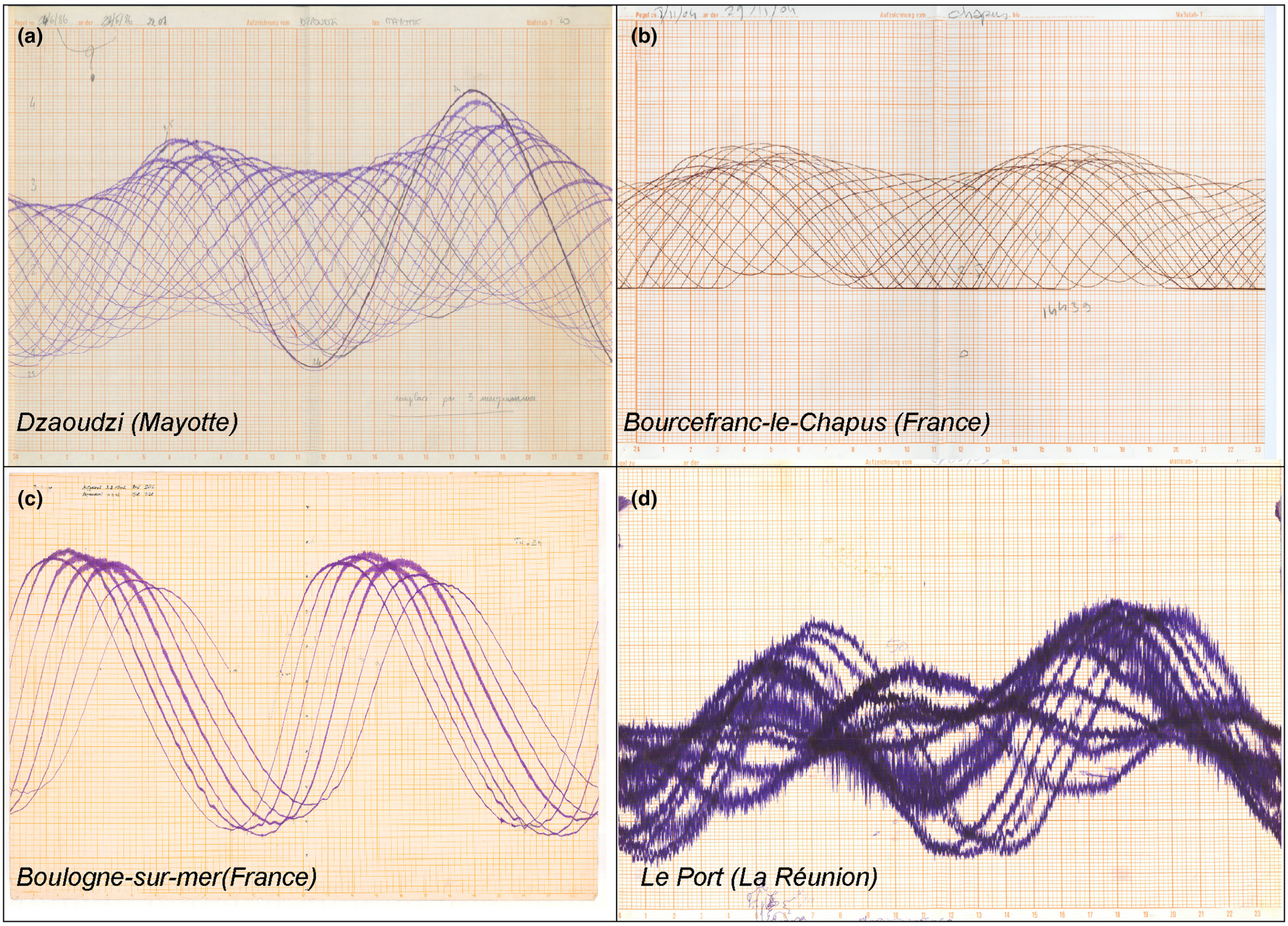

FIGURE 7 Illustrations of marigrams that can be more complex or even impossible to digitize as they are: (a) marigram having recorded more than 1 month of measurements at Dzaoudzi in 1986 with a slightly noisy signal (source: Shom); (b) another example of marigrams having recorded more than 1 month of measurements at Bourcefranc-le-Chapus in 2004 with a fine signal but with truncated low tides due to a dried up tide gauge (source: Service de Prévention des Crues – Charente-maritime); (c) marigram of Boulogne-Sur-mer with a noisy signal around high tides in 1942 (source: Shom); (d) very noisy marigram at Le port in 2007 (source: Shom)

can be linked with the scanning process to manage in spreadsheet the main information (such as the date, the information at the beginning or the end of the measurement). To deal with this type of data in spreadsheet software, it is possible to gain time and to modify after the first treatment some general information of the series as the scale, shift in time or elevation. NUNIEAU integrates tools to check the digitalization as presented in Section 4 and some feedback can be done between digitalization and tide checking.

The digitization of marigrams often requires technical expertise. Problems can include temporary or permanent datum shifts, time gaps, clock errors, insufficient or ambiguous documentation, or gauge malfunction (e.g. Talke, Familkhalili, et al., 2020; Talke & Jay, 2013; Talke, Mahedy, et al., 2020). As an example, the observer may not have transcribed on the curves the date of the measurement. In the case of 'regular' semidiurnal tides, dates can be deduced rather intuitively since the curves follow each other (Figure 2a). However, for mixed tides or microtidal sites, detection is no longer as intuitive. These deductions can only be made with knowledge of the tidal phenomenon and the characteristics of each studied site. NUNIEAU allows adding to the interface the plot of tidal predictions at the requested date. The use of predictions can therefore be an additional tool to the identification and then the digitization of tidal curves.

Compared with the transcription of tidal ledgers, the digitization of marigrams remains more complex and labour-intensive, leading to an apprehension on the part of the community to deal with this type of document and thus to the non-use of marigrams. Nonetheless, the benefits are tantalizing; the ability to obtain instrumental, high resolution data at better than hourly resolution potentially opens many research opportunities, and could allow for the reanalysis and improvement of current datasets (Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020).

Since the release of NUNIEAU, enhancements have already been developed, but there are still many improvements to be made to facilitate this step. To support this, the Sea Level Data Archaeology workshop invited the community to send updates and/or suggestions for enhancements of the NUNIEAU digitization software package to the developer.

3.3 | Ancillary data

All the metadata identified during the inventory and useful for the reconstruction of the data time series are mostly photographed or scanned.

These metadata should also be digitized in order to facilitate their subsequent processing. As presented above, there is a great diversity of the ancillary documents identified. For instance, when these metadata give quantitative information (e.g. time series of clock shifts, tide-staff readings, atmospheric pressure table, water temperature measurements, etc.), it can be digitized in the same way as tidal ledgers. The outputs of this digitization can then be considered as a new dataset.

Interpretation and evaluation of metadata records becomes more complicated and potentially ambiguous when the ancillary data include qualitative information about the gauge operation, data quality, and geophysical events such as storms (e.g. as obtained from letters between different organizations, plans, etc.). As an example, the letter available in appendix B of Ray & Talke (2019) from April of 1887 states:

"You do me an injustice in presuming that I have allowed the gauge to freeze up. It has not frozen up – the float has been entirely free from ice without a single exception. All the breaks in the curves were occasioned by the stopping of the clock. This clock has been in constant use at this station since Nov. 5, 1872, and has not been in the hands of a jeweler for repairs or even cleaning once during the whole period. I have usually taken it apart and cleaned it about twice a year, seldom stopping the clock more than 2 hr for the purpose, and taking observations from the staff to cover this. The stopping of the clock has not been occasioned by any lack of care on my part. I have given it more care and attention during the past winter than at any other time, for the reason that it was stopping. I started my fire in the tide house Nov. 14, and since the latter part of November the fire has not been out only just long enough to clear out the stove and build a new fire. I seldom leave the tide house earlier than 10 or 11 o'clock at night, and in the worst weather frequently go again before morning …."

From letters such as this, one obtains a sense for the character of the observer, which in this case suggests an extremely conscientious dedication to obtaining good quality records. On the contrary, the severe climate conditions may work against the quality of the wintertime measurements. Although there are quantitative statistical analyses that can be used to assess data quality (e.g. Ray & Talke, 2019; Talke et al., 2018; Talke & Jay, 2017), such letters provide contextual proof that can confirm such analysis, or elucidate problems that are not easily apparent in the quantitative record (see also the supplement of Talke, Familkhalili, et al. (2020); Talke, Mahedy, et al. (2020)). Judgement is needed to evaluate such records. These considerations bring out another truth: digitization and recovery of historical records are also inherently a human enterprise, and the efficacy and quality of the recovered data depend in part on the conscientiousness and perseverance of both the digitizer and the original observer.

Moreover, qualitative information is sometimes difficult to transcribe and evaluate, as there is no really established procedure to deal with this kind of documents in an efficient way in order to make them easily operable. Their treatment and analysis are processed on a case-by-case basis, depending on people in charge of the reconstruction. For example, when siltation problems are identified on a tide gauge and reported in letters or technical reports, the information can be transcribed but it is difficult to really quantify this information. We continue to rely on the judgement of scientists in data evaluation. As highlighted by the Sea Level Data Archaeology workshop, there is a need to develop guidelines for the various types of metadata that can be recovered and compile advice for the rescue of each data type.

In France, a multidisciplinary working group on "Historical Storms and Floodings" gathers engineers, researchers, statisticians and historians belonging to different organizations in order to share information on historical storms and floods in a common database (Giloy et al., 2018; Giloy & Members of the Working Group, 2021). Any book, report, archive document etc., mentioning an event is considered as a source and is integrated in the database. For a given event, the quality of a source is variable, especially if it is a primary or secondary source. Considering an 'historical' approach, a qualification scale of sources is applied and allows to make a distinction by type of storm event. The multidisciplinary approach of this group sometimes allows researchers to reconstruct or at least estimate-quantitative information from qualitative documents. Other efforts (e.g. Talke et al., 2018) have used similar methodology to gauge the reliability of historical flood marks, which are often not as reliable as instrumental measurements.

4 | CONTROL – ADJUSTMENTS – VALIDATION

This section presents the correction and validation phase of the dataset. This step is essential to obtain a temporally and vertically coherent series and is inseparable from the use of metadata.

4.1 | Removal or correction of sea level outliers

Once the raw water sea levels have been digitized, the obvious anomalies identified during digitization can be checked, corrected when possible or removed.

For measurements from tidal ledgers, errors detected often take the form of vertical jumps or spikes, affecting one or more successive measurements, and correspond in most cases to transcription errors by the observer, the historical 'tide computer' (person responsible for reducing data) or the present-day digitizer. There are different kinds of errors, including

- Error of the historical observer in reading the tide staff or automatic gauge, or in reading the marigrams axis (e.g. 1 m instead of 2 m, or 10:00 instead of 11:00 ...).
- Error during the modern data-entry process (e.g. 1.50 instead of 150 or 4.5 instead of 5.5)

When the origin of the error is identified and the correction required is unambiguous, then the data is corrected. When it is difficult to attribute a cause to the anomaly, or to define with certainty the required correction, the suspect data is deleted.

For water levels extracted from tidal charts, the most important anomalies are typically identified by visual inspection of the data during the digitization process, and by processing of the existing control sheets or tide-staff measurements associated with the measurements. When different types of data are available (staff measurements, tabulated high/low and/or hourly and marigram-based measurements), a detailed assessment of data quality is possible (Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). Reasons for anomalies cannot always be determined with certainty, but can include tide gauge malfunction, clock errors, staff measurement errors and datum shifts (e.g. to prevent the marigram data from running 'off the chart'). Examples of data issues are discussed in the supplements of Talke et al. (2014, 2018), Talke, Familkhalili, et al. (2020), Talke, Mahedy, et al. (2020).

4.2 | Data consistency

This step is essential in order to make the time series consistent in time and report it according to the same vertical datum.

Time correction

Equation of time

A first important consideration consists of checking the validity of the times in the dataset and making it coherent over the historical period of time. Dealing with long records covering several centuries involves consideration of time systems definitions. During the 19th century, tide gauges were set to different time systems: first to local times or ' mean civil time', defined by the average time that the sun reaches its zenith, at a particular longitude (see Pouvreau, 2008; Ray & Talke, 2019; Talke & Jay, 2013; Wöppelmann et al., 2006). Later, times were assigned by various conventions and laws allowing the use of a common time over large geographical areas. The measurement of time was based on what was believed to be irreproachable and immutable: the rotation of the Earth around its axis causing the apparent movement of the Sun in the sky and thus the alternation of days and nights (Pouvreau, 2008).

Thus, in order to ensure the temporal continuity of 19th-century records, it is necessary to assess whether the measurements are carried out in 'apparent solar time', 'mean solar time', local standard time, local daylight savings time or the Coordinated Universal Time (UTC). This assessment is a precondition to correctly reducing sea level observations into a standard time system for modern databases such as GESLA (Haigh et al., 2021). In more modern data, some providers (such as the US Geological Survey in the United States) provide the same data in both Local Standard Time and local Daylight Savings time, depending on time of year; these time shifts are often poorly documented, and must be assessed, for example, by comparing tidal predictions with observations. During World War II, some data series were temporarily shifted; an example is a half-hour shift apparent in the Honolulu record (Colosi & Munk, 2006).

Apparent or True Solar Time (AST) is a measurement of time based on the apparent movement of the Sun during the day. The true solar time at a given place and time is the hourly angle of the sun at that place and time. Mean Solar Time (MST) is based on a fictitious sun moving around the equator at a constant speed throughout the year. This average speed is one revolution in 24 hr. Instead of apparent time, the use of mean time did not really come into use until the late 19th century, and national and international times (like GMT (UTC)) were adopted much later still. Hence, the oldest records – HL (or HW) times from the 18th century will have been taken using AST. In France, the MST was introduced in 1816, but the transition from AST to MST was not carried out at the same time as all countries. In theory, measurements after 1816 should therefore be in MST, but in practice, the AST remained the system widely used to perform measurements until the 1890s (Ferret, 2016; Gouriou, 2012; Latapy, 2020; Pouvreau, 2008). In a letter to the French Hydrographic Service in 1893, Chief Engineer Hatt explains that The use of the AST was justified by the procedures proposed by M. Chazallon for the separation of solar and lunar waves and could be defended as such despite the disadvantages that the variability of the period generated (translated, in French in the original document).

To transform a dataset recorded in True Solar Time into Mean Solar Time, it is necessary to apply the equation of time (Bureau des Longitudes, 2011). This Equation (1) calculates the difference $E(t)$ (in minutes) between the AST and the MST:

$$E(t) = \text{MST} - \text{AST} \tag{1}$$

The numerical application of the equation below is provided by the Bureau des Longitudes, (2011) and is valid from 1900 to 2100. Over the 19th century, the variations being minimal, this Equation (2) is also applied for measurements before 1900.

$$\begin{aligned} E(t) = \; & 7.362 \sin(M) - 0.144 \cos(M) + 8.955 \sin(2M) \\ & + 4.302 \cos(2M) + 0.288 \sin(3M) + 0.133 \cos(3M) \\ & + 0.131 \sin(4M) + 0.167 \cos(4M) + 0.009 \sin(5M) \\ & + 0.011 \cos(5M) + 0.001 \sin(6M) + 0.006 \cos(6M) \\ & - 7.064x10 - 5\, t \sin(2M) + 1.46 \times 10 - 5\, t \cos(2M) \end{aligned} \tag{2}$$

with $M = 357.0363 + 0.9856\, t$ (degrees) and values of time t are in average days.

The extreme values of $E(t)$ are reached in February (+14 min) and November (−16 min) and the $E(t)$ deviation is reversed four times a year: mid-April, mid-June, early September and late December. Once the data are in MST, it is necessary to apply a correction of the longitude to transform them in UTC. In order to set the observations on the meridian of Greenwich, a calculation of the difference in longitude between this meridian and the place of the observatory is needed. For instance, a difference in longitude of 1° corresponds to a time difference of 4 min.

In the United States before the 1880s, records were generally measured in Mean Solar Time; when possible, the observer would make noon observations to check/calibrate the clock. When errors were large, or during the monthly change in marigram paper, the clock was reset (Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). In Astoria, Oregon, there are also notes and letters which indicate that a chronometer was occasionally brought up from San Francisco by steamship to more accurately check the time (Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). Later, tabulations of high/low data made by the observer were adjusted to solar time, through the equation of time. In this so-called '1st reduction', measurements were shifted to 'solar time' from mean solar time. This time shift helped facilitate evaluation and prediction of tides through the so-called 2nd reduction (Talke & Jay, 2013). In a modern context, these adjustments need to be reversed in order to harmonically analyse data (e.g. Ray & Talke, 2019).

Clock shifts

Even after applying time corrections, it can happen that time shifts or errors remain in data. Systematic timing errors can be caused by clock errors (Agnew, 1986) or could occur when tidal charts were replaced on the rotating drum by the operator without accurately resetting the drum offset to zero (Intergovernmental Oceanographic Commission/UNESCO, 1985). Apparent time shifts in the gauge can also be caused when the tide gauge malfunctions, for example when the holes in a stilling well get clogged (see e.g. Agnew, 1986; Zaron & Jay, 2014).

Mechanical clocks can vary in speed with tension in the spring and with temperature and require constant adjustment by chronometer or through sextant observations. To prevent these errors, during the installation and removal of a marigram, routine time and elevation checks were required, but not always made. Identifying siltation or clogging of the stilling well-required staff/gauge checks and could be rectified by dredging or replacing the stilling well. However, in many sites subject to siltation, dredging and other maintenance was not as regular as desirable, which necessarily impacts the quality of the data. Under such conditions, the reliability of the tide observer played an important role in gauge quality. For marigrams, if routine time checks were performed by the observer, the results of these observations were used to check the differences between observers' information and digitizing results. Furthermore, letters between headquarters and the tide observer often show that tidal hydrographers and 'computers'(workers that transcribed marigrams to tabulated data) detected anomalous data and asked observers about them (see letter from Ray & Talke (2019)). Such systemized quality assurance made it possible to identify defective periods and potentially address/fix them.

Interestingly, as highlighted in Haigh et al. (2020), the first generation of 'digital' gauges (those without paper records) in the 1960s to the 1980s were subject to timing errors which may be larger than those occurred in the 'marigram' period, when a paper record was used (Talke et al., 2018). The latter problem has been reinforced by the reduced number of routine checks that have accompanied the transition to digital instruments (Haigh et al., 2020).

Post-processing to identify and correct time errors

Sometimes, check sheets may not have been found or may be too inaccurate to provide quantitative evidence of gauge quality. In this case, several methods might be used to make a more complete quality assurance. For instance, Talke and Jay (2017) used a modified version of the technique suggested in Agnew (1986); Hudson et al. (2017). The method relies on the observation that tide gauge errors are often largest when water levels are changing the fastest; in the case of gauge clogging, the water in the stilling well was literally unable to keep up with the quickly changing oceanic conditions. Hence, if the gauge is malfunctioning, there should be a correlation between the tidal residual (the difference between the predicted and measured tide), and the time rate of change in water level dH/dt, approximated independently of the measurement from tidal predictions. Talke et al. (2018), Talke, Familkhalili, et al. (2020), Talke, Mahedy, et al. (2020) used this method to identify the magnitude of timing errors in both 19th- and 20th-century data, and were able to verify those periods of erroneous data were often during documented time periods of gauge malfunction. Similarly, Wöppelmann et al. (2014) computed time lags derived from the maximum autocorrelation obtained using the observed tide gauge signal and the tidal predictions based on the extended time series of Marseille and identified questionable periods. Ray & Talke (2019) used a combination of handwritten notes, an evaluation of tidal residuals, and the results of harmonic analysis to assess data quality.

Another way to identify time periods with clock or stilling well errors is by analysing the evolution of the temporal residuals of HW and LW (time difference between the observed and predicted HW/LW; Ferret, 2016; Gouriou, 2012; Latapy, 2020). Sometimes, the time system indicated on the scanned documents did not correspond to the system actually used during the acquisition of the measurements. There may have been confusion between AST and MST in the 19th century, or even recently during the 20th century between summer and winter time. The use of temporal residuals easily highlights this kind of error. Figure 8 gives a good example of the effects of time system confusion. In this example, the found metadata indicate that the measurements are made according to the AST, which implies the application of the equation of time: the blue curve, representing the applied time correction (Figure 8), shows the typical shape of this correction. The outputs HW/LW time residuals are in agreement with this correction most of the time (fluctuations around 0). Nevertheless, it is notable that the time correction is not appropriate for the 1878–1880 period: It increases the bias and the output residual is clearly influenced by the equation of time. In this case, although the documents found indicated that the system used was the AST, the analysis revealed that it was in fact the MST.

Once errors are identified, water levels are then corrected or removed depending if ancillary data found indicate the origin of the error. For example, when time shifts are detected and are due to technical issues, timing is then corrected from the identified shift. Sometimes, when time drifting is detected, corrections are only applied if regular time checks have taken place, allowing to make the most accurate corrections possible. In addition to the corrections, it is very important in this step to comment on the corrections applied and explain how and why the water level or the timing is modified. These comments provide a way to track the various modifications applied to the dataset.

In the case of stilling well clogging, siltation is often detected by a phase shift of high and low tides compared with

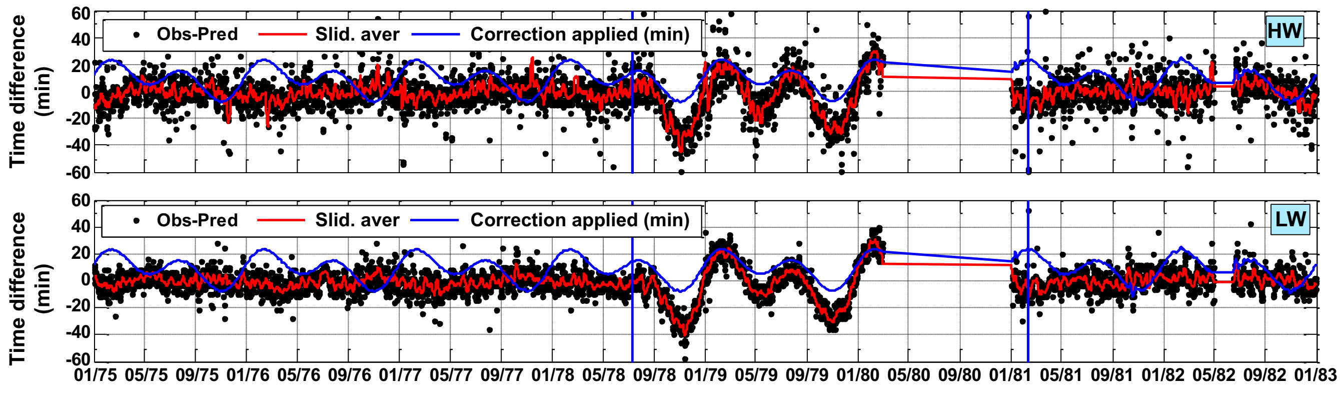

FIGURE 8 Example of temporal coherency applied at the Saint-Nazaire time series (Ferret, 2016). HW/LW time difference (Obs-Pred) and time correction applied to convert the extended dataset into UT. Corrections deduced from the information indicated on the ledgers: AST

tidal predictions. Siltation can also affect the measured water level by underestimating the real value. Depending on the degree of siltation, the phase shift and the height deviation may change, it is then difficult, even impossible, to correct the effect of siltation on the measurement. Thus, no corrections are usually made; however, as the previous example, it is crucial to indicate and communicate to end-users that the data may be incorrect. The operator's expertise is essential in this step, because it allows assigning a quality level to the data via a flag (see part 4.3.).

4.2.1 | Vertical coherency

Conversion feet/inches to metres (measurement units)
Providing vertical consistency over time is challenging and labour intensive. The first difficulty to deal with is due to unit issues: Older measurements may have been made in another system than the metric system. In the 19th century, feet and inches were commonly used. Depending on the time and the country of origin, these units are not necessarily equivalent (e.g. the value of a foot is not the same in Belgium and France [Giloy et al., 2018]).

Identification of vertical jumps/changes
An additional challenge in merging different datasets into a single consistent dataset is caused by different datum definitions. Measurements are usually referenced to the elevation of the tide gauge zero, which may however change over time. In several countries, data are linked to local hydrographic datum defined as the lowest low water of each site (Hogarth et al., 2020).

If the tide measurements were properly documented by observers over the historical time, it is possible to reconstruct the history of the hydrographic datum based on the analysis of all the metadata relative to the tide gauge found during the inventory process. For example, in Brest or Marseille, many documents were available that make it possible to ensure the vertical coherency, including information on datum changes and their relation to the instrumental zero (Coulomb, 2014; Pouvreau, 2008; Wöppelmann et al., 2006, 2008). Nevertheless, logs associated with tide observatories are often not as exhaustive as desirable, as for the Alicante and Santander sea level reconstructions (Marcos et al., 2021). Moreover, it is sometimes challenging to get information on the instrumental zero solely based on historical documents. Moreover, having a large amount of information does not necessarily make vertical coherency process easy: the documents often contain inconsistencies, and expert interpretation is often required (e.g. Ferret, 2016; Talke, Mahedy, et al., 2020).

There are several methods to identify datum changes. Most reliably, metadata can be used to construct a case history of the tide gauge and identify/account for datum shifts. Examples of such data are provided in the supplements to Talke et al. (2018), Talke, Familkhalili, et al. (2020), Talke, Mahedy, et al. (2020) and include levelling records, benchmark summary sheets, and letters referring to gauge shifts, tide-staff shifts or datum changes. Often, metadata may be inconsistent, complicating evaluation of the datum. Examples of problems include levelling errors, vertical instability in benchmarks or the gauge itself or loss or corruption of information over time. Therefore, it is often advantageous to obtain as much data as possible, from different agencies and archives (local, state and federal), to obtain multiple, consistent lines of evidence and as complete a record as possible. Using records from at least 6 different archives, Talke, Familkhalili, et al. (2020), Talke, Mahedy, et al. (2020) developed different, self-consistent interpretations of available data, considering different plausible interpretations of the same data. Combined with documented uncertainties in levelling surveys, they were able to provide confidence bounds on the datum, with the largest uncertainty evident in pre-1860 records. We recommend that archival research attempt to assess the confidence and uncertainty bounds of a datum, to enable better intercomparison of records.

Re-evaluating the datum of instrumental datasets available in PSMSL, using the case study history described above, has also revealed datum errors that occurred due to post-processing of data by tide-agencies (see also Agnew (1986)). For example, both the modern NOAA records at Boston (1921-present) and Astoria (1925-present) were offset by up to ~0.02–0.03 m and 0.05–0.06 m, respectively (Talke et al., 2018; Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). The reason was that data had been adjusted to remain constant relative to a local benchmark that was later found to be unstable. In Boston, movement of the gauge in 1939 also contributed to a datum error. Such errors in datum can be assessed by regressing the heights of benchmarks against each other, if sufficient number of repeated surveys are available over a long time period (see Burgette et al., 2009; Talke et al., 2018).

Using digitized records, several additional methods are available to identify datum problems. For example, 'buddy checking' involves the comparison of sea level records from nearby stations (Figure 9a), using either the original hourly records or daily/monthly/annual mean sea level values (Bradshaw et al., 2015; Shennan et al., 2015). Using the difference between nearby datasets provides a powerful means for spotting data errors (Figure 9b) and highlights suspicious periods (Gouriou, 2012; Hogarth

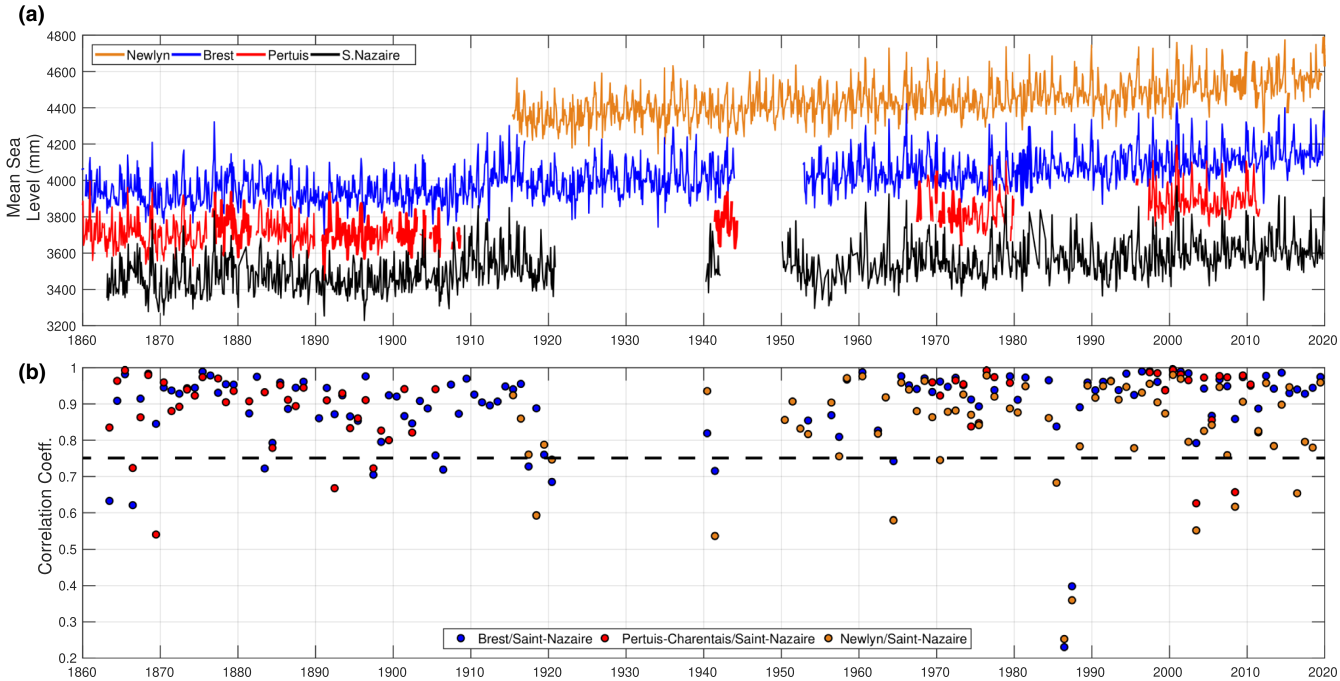

FIGURE 9 (a) Evolution of the monthly mean levels observed in Brest (source: SONEL), in 'les Pertuis d'Antioche' (Gouriou, 2012), in St. Nazaire (Ferret, 2016) and in Newlyn (source: SONEL); (b) Annual correlation coefficients between these different series

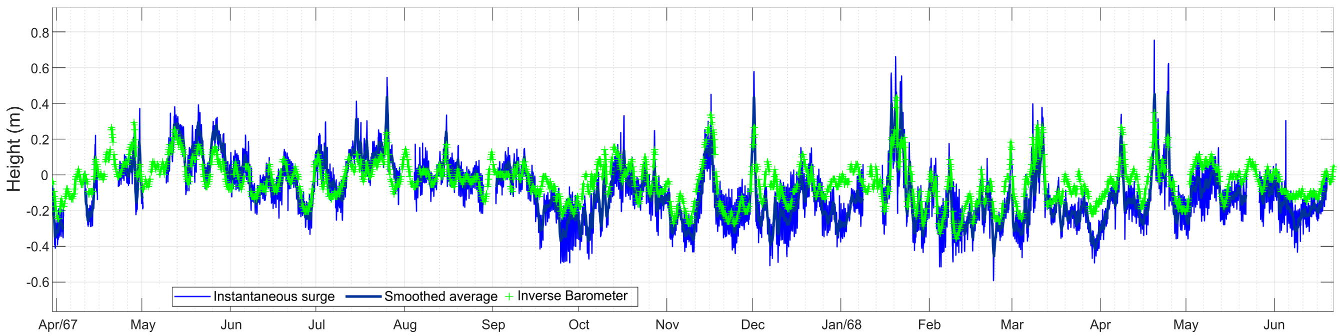

FIGURE 10 Analysis of the atmospheric pressure data from St. Nazaire between 1863 and 1894 to compare the obs-pred residuals and the effect of the inverse barometer. Here, the two series allow to verify the quality of the water level measurements at St. Nazaire between April 1867 and June 1868

et al., 2020; Marcos et al., 2021; Pouvreau, 2008; Shennan & Woodworth, 1992; Woodworth et al., 1999, 2009).

In complementary analysis, or if there are no measurements on nearby sites, another way of quality assuring the datum is to evaluate the nontidal component of the observed sea level values, that is the residual between predicted and observed sea level heights. The original purpose of this procedure is to evaluate the consistency between observations and predictions, but it also proved to be very helpful for detecting observation defects (Wöppelmann et al., 2006). In particular, taking the time derivative of the residual is helpful for identifying unrealistic changes or spikes in data (e.g. Talke et al., 2018; Talke & Jay, 2017, 2020). When weather measurements have been made simultaneously (Figure 10), residuals can be corrected for local weather effects using the inverse barometer (IB) correction which takes into account variations in sea surface height due to atmospheric pressure variations. Recently, Hogarth et al. (2020) provided a new method to improve estimates of long-term sea level trends by removing local dynamical effects from British Isles tide gauge measurements based on a barotropic, local shelf sea model and then constructing 'Common Mode' by averaging the residual signals. This combination of corrections has permitted the authors to reduce the residual variability seen on several datasets and then to identify a number of previously unrecognized vertical shifts in the tide gauge record.

Examples of vertical errors and assumptions made during the validation process

When sea level measurements were collected during hydrographic surveys, a permanent tide observatory was not necessarily installed. Usually, a tide staff was temporarily set-up on the coastline to obtain measurements simultaneously with the offshore bathymetric campaign. In most cases, an attempt was made to link staffs to land benchmarks in order to be able to re-calibrate the staffs to the same zero afterwards during a future campaign. Similarly, continuous measurements at a permanent gauge location must also be linked to one or multiple benchmarks. Hydrographic datums such as mean sea level or mean low water are then generally connected to existing geodetic networks.

Nowadays, each tide gauge and tide staff are connected to multiple permanent benchmarks (allowing the data to be referenced to a consistent land-based datum). In case one benchmark is destroyed, the zero can be reconstructed, to within survey error. As mentioned earlier, multiple benchmarks also enable subsequent evaluation of benchmark stability, allowing a stable land datum to be defined. Historical records, particularly before about 1860, often contained only 1 benchmark (if at all; Talke et al., 2018; Talke, Familkhalili, et al., 2020; Talke, Mahedy, et al., 2020). If the metadata associated with these historical measurements is lost, then it is impossible to relate the measurements to other datasets. In Dunkirk, northern France, measurements made in 1701–1702 and in 1802 (Latapy, 2020) cannot be linked to a modern datum, since no common benchmarks were found. In Astoria, Oregon, the 3 benchmarks created during the 1853–1876 historical gauge series (in 1854, 1861 and 1876) are either destroyed or no longer accessible. However, it was possible to link these benchmarks to modern ones that were monumented after 1920 using the results of levelling surveys that tied a common benchmark to the pre-1877 and post-1920 benchmarks (Talke, Familkhalili, et al., 2020;Talke, Mahedy, et al., 2020). A similar datum connection was possible for Portland, Maine back to the 1860s (Ray & Talke, 2019). These considerations show that sea level reconstruction contains both elements of science and historical methods.

During the sea level reconstruction process, assumptions have to be made and decisions have to be taken in order to reconstruct the history of the datum. For example, for Saint-Nazaire (western France, Loire estuary), doubts remained after the investigation in the metadata. For example, for the period between 1863 and 1934, the correction required to adjust raw water levels to the historical datum is between 10 and 13 cm depending on historical sources. The correction is probably constant over time, and differences of a few centimetres could be explained by inaccuracies related to the measurement (irregular surface of the dock, datum defined to the nearest centimetre in 1863 ['... 8.35 m approximately'], ...). An average offset of 11 cm was considered for this reconstruction while keeping in mind this uncertainty of 3 cm. Similarly, time variable uncertainty bounds were assigned to the datum reconstruction for Boston and Astoria, in the United States (Talke et al., 2018).

Absolute/relative sea level

The previous examples highlight that contemporaneous documents that refer to the zero of the measurement are crucial for the vertical coherency of the dataset. Such documents are then analysed to identify which zero was used, if it was attached to other benchmarks and if it is possible afterwards to connect it to other zero levels. It is also important to note that the basic assumption of this approach is that benchmarks are considered stable over time; however, this is not necessarily the case. Some sites are subject to vertical land movements due for example to dock subsidence (local impact) or post-glacial rebound (regional impact). Thus, we have to keep in mind that the sea level reconstruction process initially brings information on the relative sea level change. The newly digitized sea level dataset has to be tied to a geodetic reference system if one wants to be able to assess the absolute sea level change. This task is not easy to perform, even impossible sometimes, when measurements older than a century are considered.

Since the deployment and generalization of Global Navigation Satellite System (GNSS) technology, many tide gauge sites are now equipped with permanent GNSS receivers in order to estimate the vertical land movement affecting the tide gauge site. Vertical land movement is recognized as a critical parameter to be able to separate the land motion from the sea level change (Wöppelmann & Marcos, 2016). The GLOSS program has a dedicated portal (www.sonel.org) to provide to the users the information on the vertical land motion at the tide gauge site when a GNSS station is available. Regular levelling and systematic ties between GNSS and the tide gauge benchmarks are necessary to monitor the observatory stability (Woodworth et al., 2017). When a tide gauge has been tied to a global reference frame, it can be used to calibrate satellite altimeters. Some tide gauge observatories are dedicated sites for satellite altimeter absolute calibration such as Harvest in the USA and Corsica Island in France (Bonnefond et al., 2021). The availability of altimeter data since the 1990s has revolutionized research into ocean circulation, tides and long-term changes in MSL (Cazenave et al., 2008, 2018; Cazenave & Nerem, 2004).

4.3 | Qualification, flags and uncertainties

4.3.1 | Qualification/final check

Once the time series is temporally and vertically consistent, a final check is required to validate and qualify the data quality. This step requires some experience to isolate spikes or water levels over a longer period which may seem anomalous compared with the rest of the dataset.

For example, an isolated measurement that is 10 m higher than anything previously observed almost certainly represents an error. However, surges of a few cm or a few metres may well have been caused by the passage of a low-pressure system and should not be excluded as they can improve the estimates of extreme levels (Bulteau et al., 2015; Saint Criq et al., 2022).

During the reconstruction of a sea level time series, all ancillary documents contextualize the measurements in order to be able to validate it and finally to attribute a quality flag to it. The better we know how the measurements were performed, the better the assessment of quality of the data will be. Ideally, it is important to know the type of protocol used during the sea level measurements (devices, material, …), what were the objectives of these measurements (scientific or operational purpose, …), who were the successive observers and their precision during the measurements. These information allow afterwards to attribute a confidence index to the sea level dataset.

For example, already in 1829, Beautemps-Beaupré, the founder of modern hydrography in France, was aware that the quality of the data was highly dependent on how the measurements were done. He proposed a protocol to be implemented at each tide gauge observatory in order to obtain the best possible data quality. According to him, the possible causes of errors during water level measurements were:

1. Human error: observing the sea level seems simple, but repeating this operation at the same place every 15 min, for 6 months or more and with the supposed same rigour is really a difficult task. Alone and unsupervised, during an absence, the observer may have to interpolate heights without reporting it, so the choice of observers is important and has to be done carefully.
2. Material and climatic issues: the displacement of a tide staff, the disturbance of a watch and difficult weather conditions make measurements challenging, without even mentioning the installation of complementary tide staffs when the main one is dried out during the low water.

In order to mitigate the material problems, Beautemps-Beaupré recommended drawing a meridian at each observatory, in order to allow the observer to set his watch at noon. He must indicate on the register the amplitude of the shift day after day. Concerning the displacement of tide staff, each time, a tide staff is installed the hydrographer proposes to tie it to a fixed object. Thus, if the tide staff moved, it was easy to replace it exactly as it was before.

However, as highlighted by Hogarth et al. (2021), a 'perfect tide gauge' is influenced by a combination of factors including local tide and meteorological effects, distant ocean variability and vertical land motion (Rossiter, 1967; Thompson, 1980, 1981). Tide gauges (and observers) are imperfect, and this induce additional variability in the tide gauge records caused by discontinuities in recording methods (Woodworth, 2017) or instrumentation or datum control errors (Lennon, 2015), causing false level changes or steps in the record (Haigh et al., 2009).

Interestingly, because the 19th-century observers lived at or near the tide gauge house, tidal records from the 19th century might, in some cases, be superior in quality and/or more complete than to 20th-century measurements (Talke & Jay, 2013). Nevertheless, it is important to keep in mind that, the conditions of measurements being precarious and difficult for the observers, it is unrealistic to expect precision in the measurements comparable to the current ones (order of the centimetre and/or the minute).

For some observatories, continuous measurements were made and high/low water levels were also reported in tidal ledgers (see Section 2.1.). It is possible to use these two datasets by crossing them to identify some anomalies. By going back to the initial documents, the corrections are then applied. However, because historical high/low and hourly measurements were often rounded (e.g. to the nearest centimetre in France, or the nearest 10th of a foot in the US/UK), comparisons between modern computer-based digitization and historical tabulations will always show some differences (Talke, Familkhalili, et al., 2020;Talke, Mahedy, et al., 2020). In some cases, duplicate copies of the same data were digitized which makes it possible to identify potential transcription errors by the operator by comparing the data between them.

4.3.2 | Flags

The qualification of these data is a necessary step before any further analysis (sea level evolution, extreme levels, etc.). This action is achieved through the use of different methods (analysis of historical documents, analysis of time and height HW/LW residuals, inter-series comparisons, use of atmospheric pressure data or reanalysis to evaluate the effect of the inverse barometer) associated with a visual inspection of the data. In addition to this inspection, it was essential to regularly review the source documents (tide gauges, logs and metadata) to confirm or deny potential anomalies.

The different levels of control will allow to attribute a quality to the data, or in other words to attribute a confidence level to the data. This quality is determined from the operator's appreciation and experience. For existing French sea level reconstructions, different categories qualifying the data have been defined (according to a code inspired by what was developed during Gouriou's thesis Gouriou (2012)):

- The **flag 0**: no quality check has been performed;
- The **flag 1** has been attributed only if there are no corrections and if the difference with the prediction, and the confrontation with metrological measurements or reanalysis (when available) do not suggest any anomaly. These data are identified as 'good quality', and the current state of knowledge allows to not have any doubt about this quality;
- The **flag 2** has been used if the data have been corrected or if it presents for example a suspicion of a slight anomaly without elements for a correction. These data are identified as 'probably good';
- The **flag 3** was used when the correction gives an unsatisfactory result or is too important. In some cases, the anomaly is important without elements for correction. These data are identified as 'probably incorrect'. For some sites subject to siltation (Socoa in the SW of France), removing data likely to be impacted by siltation would mean eliminating most of the available extended time series (Khan et al., in prep) However, even if siltation can cause a significant difference between LW observations and predictions (overestimation or dephasing), these measurements can nevertheless be used in the study of extreme levels.
- The **flag 4** has been attributed when there is no doubt that the data is of 'poor quality'. The data are therefore removed from the dataset.

Flags can be used afterwards to select only certain qualities according to the type of analysis one wants to do. For example, mean sea level studies require the use of data with good vertical quality and the best possible precision on the zero position. For studies on the evolution of the tidal range, we do not necessarily need vertical references, so it is possible to use data with a greater uncertainty on the zero of the measurement.

4.3.3 | Uncertainties

Once an observation has been made, it requires recording, sending and collating into global digitized records. At all of these stages, either errors or deliberate modifications to the raw data can be incorporated (Thorne et al., 2005). The contextual metadata knowledge can prevent misinterpretation of long-term patterns by discriminating between natural physical and anthropogenic effects in historical sea level time series analyses, but the quality control process expertise taking into account this information is often lost in separate log files. In order to improve the qualification of the data, it is important to be able to attribute an uncertainty to the data related to the history of the observatory and based on the devices used, errors induced by operators, siltation, datum uncertainty, etc.

Sea level uncertainties may have different origins that can be due to:

- The equipment and procedures used to achieve sea level measurements (tide-staff, float/radar tide gauge);
- Errors induced by the operator (tide-staff reading or retranscription);
- Errors induced by the digitization process;
- Uncertainties due to the assessment of the tide gauge datum and
- Uncertainties linked to the observatory or meteorological conditions (suspected offsets or siltation of the stilling well).

All these uncertainties are usually considered to be independent of each other.

This work of estimating uncertainties on historical data was undertaken with meteorological data. Among others, Gallego et al. (2007) analysed historical data for wind, atmospheric pressure and air temperature for the city of Cádiz for the period 1806–1852 and tried to estimate the uncertainties involved in the measure of the pressure. Historical series present large uncertainties in the location of the barometer, and sometimes, the location and altitude of the instrument in the city are unknown. In this regard, the uncertainties in the metadata associated with both historical pressure series make it difficult to interpret the differences that can be related to non-documented changes in the location or type of barometer.

Consequently, estimating the uncertainty involves complex considerations, because any measurement is subject to several different sources of error, or 'effects' (Mittaz et al., 2019).

The actual challenge is to identify, integrate and model uncertainties depending on their origin. As an example, for a similar type of data, Brohan et al. (2006) and Morice et al. (2012) estimate uncertainties from historical temperature records (1850 onward) by combining each error component. In their studies, uncertainties in the land surface temperature dataset can be divided into three groups:

(a) station error, the uncertainty of individual station anomalies; (b) sampling error, the uncertainty in a grid box mean caused by estimating the mean from a small number of point values; and (c) bias error, the uncertainty in large-scale temperatures caused by systematic changes in measurement methods.

These studies assess a comprehensive set of uncertainties to accompany the gridded temperature anomalies. However, the authors acknowledged that a definitive assessment of uncertainties is impossible, because it is always possible that some unknown error has contaminated the data, and no quantitative allowance can be made for such unknowns (Brohan et al., 2006).

5 | INTEGRATION OF RESCUED DATASETS INTO INTERNATIONAL SEA LEVEL DATA REPOSITORIES

The final objective of data rescue is to make recovered sea level datasets available for scientific and engineering uses and applications. As most of sea level data rescue projects are limited to one or a couple of sites, the vetting of these historical records is generally done through scientific publications (a non-exhaustive list is presented in Section 1.6).

In the last decade or so, new types of peer-reviewed data publications have appeared. Such journals increase the visibility of research data and data rescue, and reinforce their status as a scientific contribution, in the same way as 'classic' publications.

Best practice in the publication of a data paper requires making the dataset accessible, either by depositing it in a Research Data Repository or by including data as an appendix or supplement. A Research Data Repository is a database designed to host, store, make visible and accessible research data. Its role is to allow the depositing of data, its description, its access and its sharing for re-use. Each repository generally has a meta-data policy for the deposit, description and dissemination of data. The ideal is for a user to have access to both the raw digitized data, the final dataset and the corrections and adjustments made to develop the final validated dataset. Sometimes, the processing codes are thus provided.

Another method by which historical data are disseminated is through databases that concatenate data from many sources. Such databases are also an effective archiving tool for both modern and historical records. For example, the GESLA (Global Extreme Sea Level Analysis) dataset provides a comprehensive database of hourly tidal records from around the world in a common format (Haigh et al., 2021). The third version of GESLA, available since 2021, more than doubled the years of available records. Each dataset is supplied by 36 international and/or national organizations. The common format has enabled many regional or global studies of tides, extremes and sea level (Haigh et al., 2021).

The GESLA-3 database has also become a repository for digitized archival records. At present, approximately 1% of the 5,119 datasets starts before 1900. Additionally, 29 datasets stem from exercises in data archaeology. However, many historical records remain undocumented, undigitized or otherwise unavailable (Haigh et al., 2021); additionally, the database does not yet include HL records or other types of water level records. Therefore, sea level data rescue efforts and data accessibility remain vital for improving 19th- and 20th-century data coverage.

6 | CONCLUSION

Over the last two centuries, historical tidal records were collected in coastal regions all around the world. However, long-term sea level data series are rare and the measurements unrepeatable (Bradshaw et al., 2015). These records make a vital contribution to climate studies (sea level rise), oceanography (ocean currents, tides, surges), geodesy (national datum), geophysics and geology (coastal land movements) and a number of other disciplines. Recently, more and more sea level reconstruction projects have been initiated; however, they are often limited to one site or region due to the lack of time and resources.

As there are no existing national/international structures or global projects in sea level data rescue, in 2020, the Workshop on Sea Level Data Archaeology was held to bring together experts active in these activities. Several recommendations were made during the workshop, including the importance of developing definitions/guidelines for the various types of observational and metadata that can be recovered (e.g. marigrams, high and low water measurements and hourly observations) and developing guidance for the rescue of each data type. In this context, this article reviews the sea level data archaeology process by detailing the different sea level reconstructions steps (inventory, scanning, digitization, validation and qualification) and by also showing many examples of the types of documents that can be found.

There is also a need to compile inventory of data rescue tools (e.g. Nunieau software and any other software that facilitates the digitization or processing of data) and facilitate sharing of best practices with the idea of promoting this type of project. Moreover, the workshop identified some basic requirements for the quality control of rescued data that are presented in this article. The workshop also recommends that a 'raw' version of a dataset as well as a quality-controlled version for processing be stored together alongside lineage metadata that describes and documents any processing the dataset has undergone.

The importance of keeping all the different steps of the process is essential in order to allow future scientists to know the origin of the correction and to be able to modify it in the case of an error or the addition of new information. It would also be useful to build a list of archives and historical sources that have already been searched in order to avoid duplicated effort, and to highlight where further data rescue efforts may be needed.

Archival data rescue, digitization and collation of metadata is difficult and still rare due to the labour-intensive process of obtaining, digitizing and interpreting historical records. However, technological advances may enable improvements to the digitization process, either through citizen science projects or through machine learning and optical character recognition techniques. These methods may improve the quality and speed of data digitization.

Our review shows that the reconstruction process combines scientific skills (knowledge of the tidal phenomenon) and historical expertise (in the comprehension of the metadata). For the oldest data, it is essential to understand the context of the time in order to attribute quality and confidence to the measurement, particularly when qualitative data are considered. To this end, multidisciplinary working groups are increasingly emerging (Giloy & Members of the Working Group, 2021). As the workshop also recommended, the collaboration between 'hard science' and humanities and social sciences makes it easier to develop usable information.

AUTHOR CONTRIBUTIONS

Alexa Latapy: Investigation (equal); visualization (lead); writing – original draft (lead); writing – review and editing (equal). **Yann Ferret:** Conceptualization (equal); validation (equal); writing – original draft (equal). **Laurent Testut:** Investigation (equal); validation (equal); writing – original draft (equal). **Stefan Andreas Talke:** Methodology (equal); resources (equal); visualization (equal); writing – review and editing (equal). **Thorkild Aarup:** Writing – review and editing (equal). **Frederic Pons:** Software (equal); visualization (supporting); writing – original draft (equal). **Gwenaële Jan:** Writing – review and editing (supporting). **Elizabeth Bradshaw:** Resources (equal). **Nicolas Pouvreau:** Methodology (equal); validation (equal); writing – review and editing (supporting).

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