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Peskas: Automated analytics for small-scale, data-deficient fisheries

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ABSTRACT

Small-scale fisheries account for almost 90 % of global fisheries employment and are responsible for landing >40 % of the world's fish catch. Yet their importance to livelihoods and food and nutrition security in Least Developed Countries are only recently emerging due to the logistical, financial, and capacity challenges of gathering and interpreting data in this diverse, dispersed and informal sector. Peskas was designed as a low-cost solution to tackle this problem, providing a template workflow for ingestion and analysis to a decision dashboard, which can be adapted to different contexts and needs.

Metadata

Nr	Code metadata description	*Please fill in this column*
C1	Current code version	peskas.timor.portal v1.0.0 peskas.timor.data.pipeline v3.1.0
C2	Permanent link to code/repository used for this code version	portal: https://github.com/WorldFishCenter/peskas.timor.portal pipeline: https://github.com/WorldFishCenter/peskas.timor.data.pipeline
C3	Permanent link to reproducible capsule	portal: https://doi.org/10.5281/zenodo.10906764 pipeline: https://doi.org/10.5281/zenodo.10906697
C4	Legal code licence	Apache License
C5	Code versioning system used	git
C6	Software code languages, tools and services used	R, HTML, python
C7	Compilation requirements, operating environments and dependencies	portal: https://github.com/WorldFishCenter/peskas.timor.portal/blob/main/DESCRIPTION pipeline: https://github.com/WorldFishCenter/peskas.timor.data.pipeline/blob/main/DESCRIPTION
C8	If available, link to developer documentation/manual	https://worldfishcenter.github.io/peskas.timor.data.pipeline/
C9	Support email for questions	peskas.platform@gmail.com

1. Motivation and significance

Small-scale fisheries (SSFs) lack a clear global definition, but are characterised by low-impact fishing methods, their importance to local and coastal economies and cultures, and their reliance on local ecological knowledge and sustainable practices in nearshore and coastal environments. These fisheries contrast with large-scale, industrial operations in terms of the technology used, their ecological impact, and economic motivations. Small-scale fisheries account for >40 % of the world's fish catch, and (in 2016) were estimated to employ 1.9 % of the globally employed population (1 out of every 50 jobs worldwide) [1]. Yet their importance to livelihoods and food and nutrition security in Least Developed Countries are only recently and slowly emerging due to the logistical, financial, and capacity challenges of gathering and interpreting data in this diverse, dispersed and informal sector [2–4]. >90 % of small-scale fishers and fish workers are in low- and middle-income countries of the global south [5], and this corresponds to a lack of institutional capacity and low political will to prioritise small-scale fisheries [4]. Only recently, targeted research has illuminated the value and contributions of this mostly invisible sub-sector in dimensions of food and nutrition security [6], production and economic value and livelihoods, gender inclusion and equality, and governance [1]. There has also been a concerted advocacy to promote inclusion of small-scale fishers and fisheries in global agendas and dialogues around

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the blue economy, initiated through the creation of the Voluntary Guidelines for Securing Sustainable Small-Scale Fisheries in the Context of Food Security and Poverty Eradication (SSF Guidelines) [7], the International Year of Artisanal Fisheries (2022), and the COFI subcommittee on Fisheries Management focusing on the importance of fisheries in ending poverty, hunger and malnutrition [8].

The SSF Guidelines state that “All parties should promote the availability, flow and exchange of information, including on aquatic transboundary resources, through the establishment or use of appropriate existing platforms and networks at community, national, subregional and regional level, including both horizontal and vertical two-way information flows. Considering the social and cultural dimensions of SSFs, appropriate approaches, tools and media should be used for communication with and capacity development for small-scale fishing communities” [7]. Sustainable Development Goal 9c calls to “significantly increase access to information and communications technology and to strive to provide universal and affordable access to the Internet in least developed countries by 2020″ [5].

The challenge of measuring and understanding the dynamics of an underwater and highly mobile resource (e.g. fishes) to achieve sustainable management outcomes, places a demand on fishers and vessels for data. Peskas is a response to this challenge, as a digital application that facilitates the transfer, validation, analysis, and visualisation of SSF catch and effort data, marking a significant step towards leveraging digital technology for environmental and financial sustainability. The development of Peskas was primarily driven by the critical need to address the data scarcity in SSF, which are instrumental in global fish production yet lack comprehensive data collection and analysis mechanisms.

The Peskas software was initially piloted and refined in Timor-Leste, a small island developing nation, showcasing its adaptability and scalability in a real-world context. The design principles of Peskas — open-source accessibility, component-based flexibility, integration of vessel tracking with catch records, and the capability for detailed spatial and temporal analysis — make it uniquely suited for enhancing SSF data management. Additionally, its user-friendly dashboard, co-designed with fisheries scientists and government managers, allows for straightforward data interpretation, aiding decision-making processes for fishers, managers, and researchers alike.

Fisheries-dependent data (catch volume, composition and fishing effort) are the foundation of environmental (and fisheries) sustainability, and on which rests the decision-making of stakeholders at various levels of influence and knowledge. Yet, the data and the systems to support informed decision-making are absent from the small-scale fisheries sectors in least-developed countries. We addressed this issue by utilising open-source software tools to develop Peskas; a digital platform that is both adaptable and scalable, facilitating the aggregation, categorization, analysis, and visualisation of data related to the catch and effort of small-scale fisheries.

2. Software description

Peskas is a software designed to turn fisheries data into insights for decision-makers and stakeholders. Small-scale fisheries data can include information about the fishers and indicators of their livelihoods and income, the number and type of vessels involved, where these vessels and/or fishers go, the fishing gears they use to catch fish and invertebrates, and the composition of their catches such as the species, number of individuals, and their market value. Peskas manages these data from their collection at landing sites to visualisation and publication of fisheries trends, statistics and insights on a decision dashboard and in automated reports. It utilises an automated digital infrastructure to process and visualise fisheries data, helping researchers and stakeholders gain knowledge and insights that can inform data-driven decisions for sustainable fishery management and be used in various publications such as articles, reports, and notes. The system is designed for a wide range of users, including fisheries managers, policymakers, researchers, and technical staff. The following subsections describe the Peskas’s architecture and functionalities in detail.

2.1. Software architecture

Peskas is composed of two core R packages, one dedicated to the data workflow, peskas.timor.pipeline [9] and one intended for visualisation, peskas.timor.portal [10]. The R language was selected for its powerful statistical computation and graphical capabilities conducive to data analysis tasks. Docker containerization is a cornerstone of the architecture, ensuring platform independence and streamlined deployment across diverse environments. Version control and automated workflows are managed through GitHub and GitHub Actions, supporting continuous integration and deployment practices, while Google Cloud Platform is used for data storage. For interactive data visualisation, a Shiny web application based on a Bootstrap 5 UI kit (Tabler) and running on Google Cloud Run is employed to construct a dynamic, multilingual web application, whereas Rmarkdown is utilised to generate detailed reports integrating both analysis and outputs. The curated Peskas data are open access, archived in the Harvard Dataverse storage repository automatically via the Dataverse Application Programming Interfaces (API).

The architecture of Peskas was designed to minimise costs as far as possible, and to be adaptable and scalable, allowing for flexibility and ease of maintenance. From data collection and preprocessing to analysis, validation, and dissemination, each step runs within a Docker environment, ensuring consistency and reproducibility. The use of GitHub Actions automates the entire pipeline, enabling daily updates to the data and visualisations provided by the portal. Fig. 1 illustrates this architecture of the Peskas platform which ensures all components work together seamlessly, providing reliable, scalable, and insightful analytics for fisheries management.

2.2. Software functionalities

The Peskas platform is engineered to deliver a comprehensive array of functionalities that streamline the collection, processing, analysis, and presentation of fisheries data. This multifaceted approach not only enhances the utility of the platform for various stakeholders but also ensures the integrity and accessibility of the data, as the following subsections describe. Peskas consists of six core modules, each dedicated to a particular data flow step and consisting in turn of a series of functions:

1. **Data Collection**: KoBoToolbox, an open-source suite of tools for field data collection, is used to collect digital surveys in challenging environments with limited internet connectivity. Peskas pulls the data from the KoboToolbox database in near real-time that are collected from small-scale fisheries landing sites. Secondly, solar-powered GPS vessel trackers are used to collect continuous (every 6 s) geolocation data from assigned vessels.
2. **Pre-processing**: Data formatting, shaping, and standardisation to prepare the raw data for analysis.
3. **Validation**: Outlier detection and error identification with an email alert system to ensure near-real time maintenance of data quality.
4. **Analytics**: Modelling fisheries indicators, nutritional characterization, and data mining to extract valuable insights.
5. **Data export**: Automated dissemination of processed and analysed fisheries data to ensure accessibility and comprehension. This involves restructuring data for dashboard integration and open publication.
6. **Visualisation**: Tools for data reporting and sharing of insights through a comprehensive dashboard.

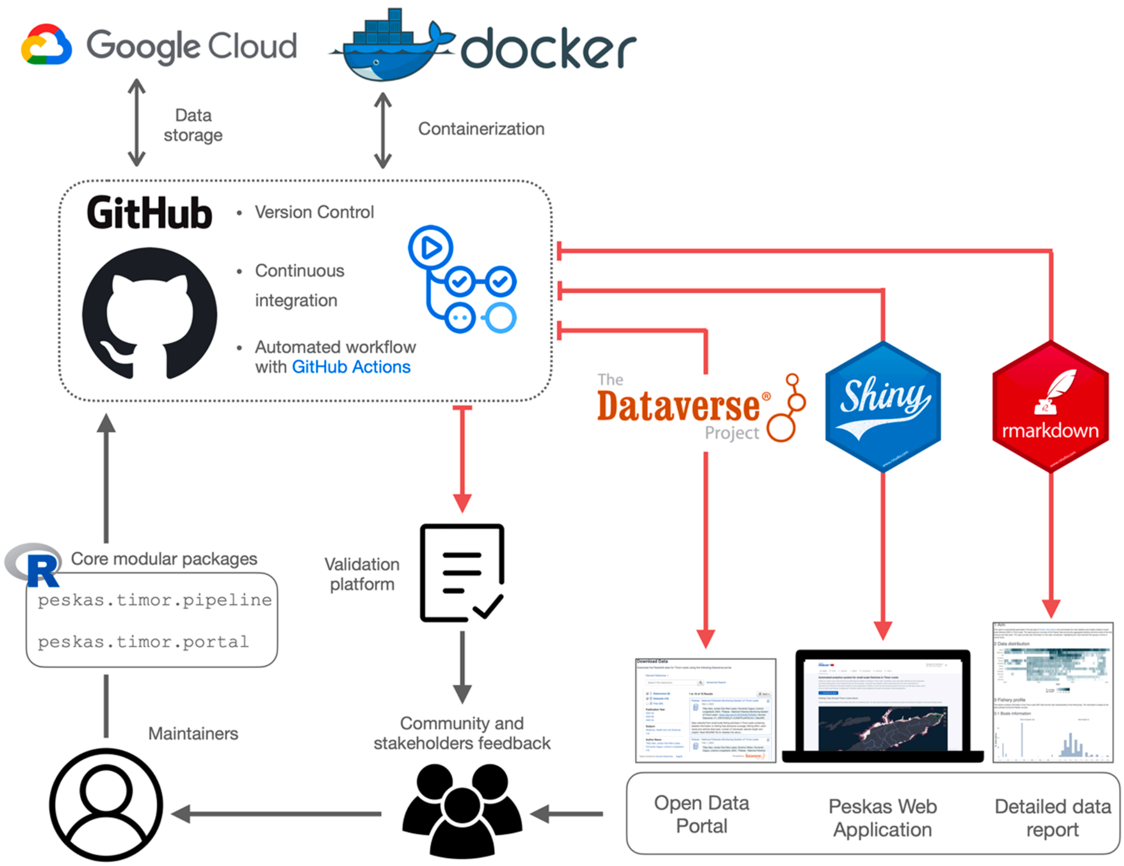

Fig. 1. Schematic representation of the Peskas software infrastructure, showing the integration of the two core R packages (peskas.timor.pipeline and peskas.timor.portal) with various services for robust data management and dissemination. Google Cloud serves as the data storage solution, while Docker ensures containerization. Version control and continuous integration are managed through GitHub, augmented by an automated data pipeline that runs via GitHub Actions. The validation platform enforces quality assurance, which, combined with community and stakeholders' feedback, informs maintainers on the ongoing development and needs. Main outputs (red arrows) are funnelled into a dedicated open-source data portal, the interactive Peskas web dashboard, and detailed data reports, facilitated by the Harvard Dataverse Project, Shiny, and R Markdown respectively.

2.2.1. *Data collection and integration*

A key functionality of Peskas is its capability to automate the retrieval of data from a wide range of sources. The entry points for data into Peskas include digital catch surveys with fishers as they return to shore, vessel trackers that record GPS data, and static fishery data such as the number of boats per municipality, which is obtained from the government registry of fishing vessels. This combination of dynamic and static data initiates the data flow into the Peskas pipeline, enabling comprehensive fisheries data analysis. Peskas leverages APIs such as the one provided by KoBoToolbox to automate the retrieval of survey data (Table 1). While KoBoToolbox is a key tool for digital field data collection in diverse environments, Peskas is designed to work with any similar XForms or data collection platform. For tracking vessel movements, Peskas integrates with Pelagic Data Systems (PDS), which offers a vessel tracking system (hardware) and data-as-a-service solution for monitoring fishing vessels. This yields high-resolution data on vessel movements. However, Peskas's architecture is built to accommodate data from any tracking system that provides compatible data formats, ensuring flexibility in sourcing vessel movement data. The automated integration of tracking data into Peskas enriches the dataset with high-resolution geolocation and movement information, enabling the calculation of fishing effort per boat and extrapolation across municipal and national fleets. Beyond these specific integrations, Peskas currently

Table 1
Peskas core information collected at Timor-Leste fishing landing sites.

Variable	Description
Landing date	Date on which catch is landed from a fishing trip
Site	Name of the location at which boats land their catch
Gear	A tool or method used to catch fish, such as hook-and-line, trawl net, gillnet, pot, trap, spear, manual collection etc.
Propulsion gear	Method used to propel a watercraft, can be motorised or unmotorised
Habitat	Ecological habitat where the capture was made
Trip length	Duration of fishing, measured in time (hours)
Fishers number	Number of fishers involved in the fishing trip
Fuel	the volume (L) of combustible fuel used during a fishing trip to drive an outboard or inboard engine on a motorized fishing vessel
Catch taxon	ISSCAAP codes identifying the taxa group (https://www.fao.org/fishery/en/collection/asfis/en)
N. individuals	Number of fishes (invertebrates) in the catch
Catch length	Average length of the fishes (or invertebrates) in the catch (cm)
Catch price	The estimated revenue from selling the catch (USD)
Catch preservation	Methods of preserving the catch inshore and offshore

Note: derived variables such as catch weight, nutrient composition, and fishing effort are calculated from these core variables but are not included in the table. Definitions include standardised terminology from the Aquatic Foods Ontology [9].

utilises Airtable[3] as the preferred platform for its metadata registry, including static tables with vessels, catch, and regional information used for the subsequent data processing steps. This approach ensures that Peskas remains a versatile tool for data collection and integration, capable of working with a broad spectrum of data sources and types.

2.2.2. Preprocessing

Once the data is collected, Peskas initiates a preprocessing phase where the raw data undergoes cleaning, normalisation, and transformation. This phase standardises data formats, ensuring uniformity and converts data into tidy formats. It also involves a preliminary quality check for inconsistencies and missing values. One of the challenges addressed during this phase is the integration of data collected via three distinct survey versions of KoboToolbox. These versions, each with its unique structure, necessitate being merged to achieve a unified data framework. After the merging of the KoboToolbox data, the pipeline triggers two pivotal data-mining functions: `get_weight` and, subsequently `calculate_nutrients`. These functions extract information regarding the weight of each catch and its nutrient composition, respectively. These functions pull data from FishBase [10], a comprehensive external resource, by employing an API. This integration allows for the dynamic inclusion of length-weight relationships and nutrient concentration information based on the most updated information. Moreover, this stage involved the alignment with the established aquatic foods ontology [9], where variables are not only renamed for enhanced clarity but are also aligned with a recognized and controlled vocabulary where applicable.

2.2.3. Validation

In the validation module of Peskas, data undergoes a rigorous validation process to ensure its accuracy and consistency for subsequent analyses; it involves the validation of both catch and vessel movement data. For catch data, the process involves the examination of outliers and anomalous values, which when identified are excluded from further analysis. The validation procedure is organised through a systematic labelling process, wherein each data entry is assigned a specific code that reflects a particular validation status. For instance, data entries without outliers are tagged with the code "0," indicating "no alerts." Conversely, a code "5″ signals that the "Trip duration is too long," and a code "7″ denotes that the "Recorded length is too large for the catch type," among others. In total, 21 distinct alert flags have been established, each addressing a specific and critical dimension of the data to facilitate a comprehensive quality assessment. The decisions on how to structure data alerts took place through dialogue with local stakeholders and fisheries experts to ensure they were context specific.

Validation employs both univariate and multivariate methods to detect outliers and assess the data precision. Univariate outlier detection is conducted using the median absolute deviation (MAD) method, in the “univOutl” package [11]. Multivariate approaches are employed to verify the accuracy of specific variables, such as catch weight, where outliers are identified using thresholds based on Cook’s Distance of the residuals between catch weight and catch value.

To refine outlier detection accuracy and fine-tune detection parameters, entries flagged as potential outliers undergo manual scrutiny on a specialised validation platform. This internal tool, a Google Sheet integrated with Kobotoolbox via Google Apps Script, streamlines the review process. This setup facilitates a more efficient and effective manual validation step, especially from the stakeholder’s perspective, ensuring that outlier detection is both precise and adaptable to the nuances of the data. The final product of this validation module is a data frame that has been meticulously cleaned and validated, ensuring its readiness for further analysis and processing in modelling and metric extraction phases.

Vessel movement data validation focuses on the unique challenges associated with global position data. Issues such as undetected trips, merged trips, or split trips, as well as potential delays or losses of information due to poor network coverage, necessitate a tailored validation approach. The `validate_pds_data` function is instrumental in addressing the complexities associated with GPS tracking data, by evaluating each vessel trip for its duration and the distance covered. This evaluation utilises specified parameters to assess the durations and distances, along with the distance between the start and end points of a fishing trip. Importantly, it also incorporates quality metrics to refine data quality. Among these metrics, “outlier limits” identify and exclude data points that markedly deviate from expected patterns, such as anomalously high speeds, indicating potential inaccuracies or anomalies in the data. Similarly, “signal trace dispersion” measures the consistency and reliability of GPS signal locations over time, where a high dispersion level could suggest issues like poor GPS signal quality or errors in data transmission.

2.2.4. Analytics

In the analytics module of Peskas, following data validation, the focus shifts towards quantifying fisheries indicators. This module is tasked with estimating the average catch per trip as well as the average revenue per trip across municipalities. Also, we estimate the number of landings per fisher by month derived from a generalised linear mixed model. At the heart of this module, the `estimate_fishery_indicators` function orchestrates the workflow, beginning with the ingestion of trip data, which is then enriched with metadata on registered boats.

Since 2018, Peskas has used 479 GPS devices distributed across various municipalities in Timor-Leste, covering an average of 15 % of the total fishing vessels within these areas. These devices continuously collect high-resolution geolocation data, enabling the modelling of fishing trips on weekly, monthly, and annual bases for each municipality. By integrating this trip data with the total number of fishing vessels per municipality from MAF registry, Peskas estimates the overall fishing effort. This methodology allows for scaling average catch and revenue per trip to a regional level, and thus national, providing an overview of fisheries activities beyond the directly monitored vessels. Furthermore, catch estimates are performed not only on aggregated values but also across different fish groups and key species. This disaggregation enhances the understanding of species-specific trends and their implications for fisheries management. This approach adds a critical layer of granularity; by dissecting the catch data into specific taxa, the module enhances the understanding of species-specific trends and their implications for fisheries management.

2.2.5. Data export

The export module in Peskas disseminates the processed and analysed fisheries data to a wider audience, ensuring both accessibility and usability. This module undertakes a data restructuring process aimed at fulfilling dual objectives: firstly, to align with the dashboard framework for visualisation and user interactions, and secondly, to prepare the data for open publication. For open publication, both raw and aggregated (national and municipal) data undergo conversion from RDS file format to CSV. This transformation caters to the needs of a general audience, facilitating broader access and understanding. Accompanying the data, an informative README document is automatically generated, offering detailed descriptions of the data content and fields. Data is uploaded to the Harvard Dataverse portal under the CC BY-NC-SA 4.0 licence through the portal API service, automatically, every month (https://dataverse.harvard.edu/dataverse/peskas). This automated process ensures that the latest fisheries data are consistently made available to researchers, policymakers, and the public. Peskas digital catch surveys

[3] Airtable was chosen here because it allows us to retrieve data in a programmatic manner, while still allowing us to edit it without the need for another editing interface. Airtable could be substituted with a database, google sheets, or (e.g.) CSV files committed to GitHub.

and vessel tracking are entirely voluntary on the part of the fisher. Peskas also ensures that sensitive data, such as personally identifiable information or commercially valuable data, is anonymized and aggregated before being shared.

2.2.6. Visualisation and reporting

To make the insights accessible and actionable, Peskas boasts an advanced visualisation feature through an interactive Shiny dashboard. This dashboard serves as the primary interface for users to explore, analyse, and interpret the data in real time. It is complemented by the capability to generate detailed reports using Rmarkdown, which allows for the dynamic incorporation of analysis results, including charts and tables, into comprehensive documents (Fig. 2).

2.3. User interface

The Peskas portal (https://peskas.org/) provides general information on the Peskas initiative. The Timor-Leste dashboard (https://timor.peskas.org/), is a robust web application hosted on Google Cloud Run, ensuring scalability and reliability. It leverages a suite of R packages to deliver a dynamic, interactive user experience, particularly in visualising fisheries data. The dashboard is updated daily with fresh data from the peskas.timor.pipeline, orchestrated through GitHub Actions, ensuring that the displayed information is real-time and actionable. Developed using the Shiny framework, the portal incorporates advanced visualisation tools such as "kepler.gl", a powerful Javascript library for geospatial data *analysis*, which is used to provide stakeholders with a visual understanding of fishing activity distributions across Timor-Leste.

The user interface is designed to be intuitive and accessible, featuring a multilingual option that currently includes English, Portuguese, and Tetum. This feature is crucial for engaging local communities in sustainable fisheries management by allowing them to access and analyse data in their preferred language. Data interaction is facilitated by various R packages integrated into the portal, such as "reactable" for interactive tables [12], and "apexcharter" for responsive charting solutions [13]. These tools enable users to drill down into specifics such as catch volumes, species distribution, and fishing efforts, with the flexibility to customise views and download data according to their needs. The portal's backend is supported by Google services, with authentication managed via "googleAuthR" [14] and data storage solutions provided through "googleCloudStorageR" [15], ensuring secure and scalable cloud storage options (Fig. 3).

3. Impact

Timor-Leste is one of the smallest, newest and poorest countries in the world, having regained independence from Indonesian occupation in 2001. Newly independent Timor-Leste emerged into a situation of chronic poverty and malnutrition, and extremely limited governance capacity and infrastructure [16,17]. Yet, the country has garnered recent attention from researchers and fisheries stakeholders around the world as having adopted the most sophisticated, near-real-time monitoring system for small-scale fisheries [18].

In 2011, the Government of Timor-Leste signalled their intention to leverage the potential of fisheries in eliminating poverty and malnutrition [19], but the sustainable growth of the sector relied on information that was not available. Not only was there no data, but also no system or the capacity to collect, analyse or use it to make decisions. As such, Peskas was developed in response to a specific need. To ensure it was relevant, contextualised and fit for purpose, it was co-designed with fisheries officers and has been iteratively updated in response to targeted and anecdotal feedback from government officers, researchers, and fishers since 2017.

The first version of Peskas was used to guide the drafting of the National Fisheries Strategy in 2018 [20] and the revision of the National FIsheries Law. Six years on, where before almost no quantitative research could be undertaken due to the dearth of data, Peskas has now encouraged and enabled empirical and experimental research in fisheries in Timor-Leste [21,22] and data extrapolations have provided the first national catch estimates for FAO reporting since 2018 [23]. Peskas offers a near-real-time monitoring system that provides detailed insights into fishing trends over time and space, and this has brought answers to long-standing research questions about fisheries activity patterns, seasonality, important fishing grounds, and safety at sea concerns.

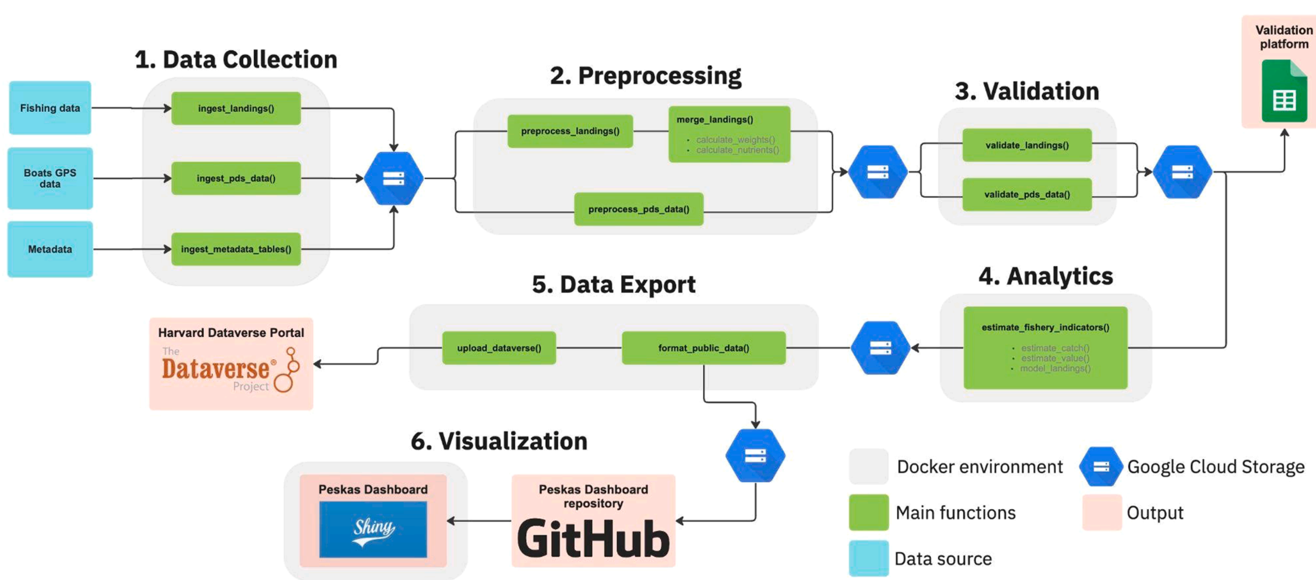

Fig. 2. A schematic representation of the six modules of the Peskas workflow. The workflow is initiated by data collection (1), which encompasses automated ingestion of fishing data, vessels' GPS data, and metadata. This is followed by data preprocessing (2), where landing data are merged and processed to calculate weights and nutrients. Subsequent stages include data validation (3), analytics for estimating key fishery indicators (4), and data export (5), where the data is formatted for public use and uploaded to the Harvard Dataverse Portal. The final stage (6) involves the visualisation of validated data through the Peskas Dashboard, providing an interactive platform for data exploration and reporting. All modules operate within a Docker environment, with Google Cloud Storage utilised to store outputs that trigger subsequent modules.

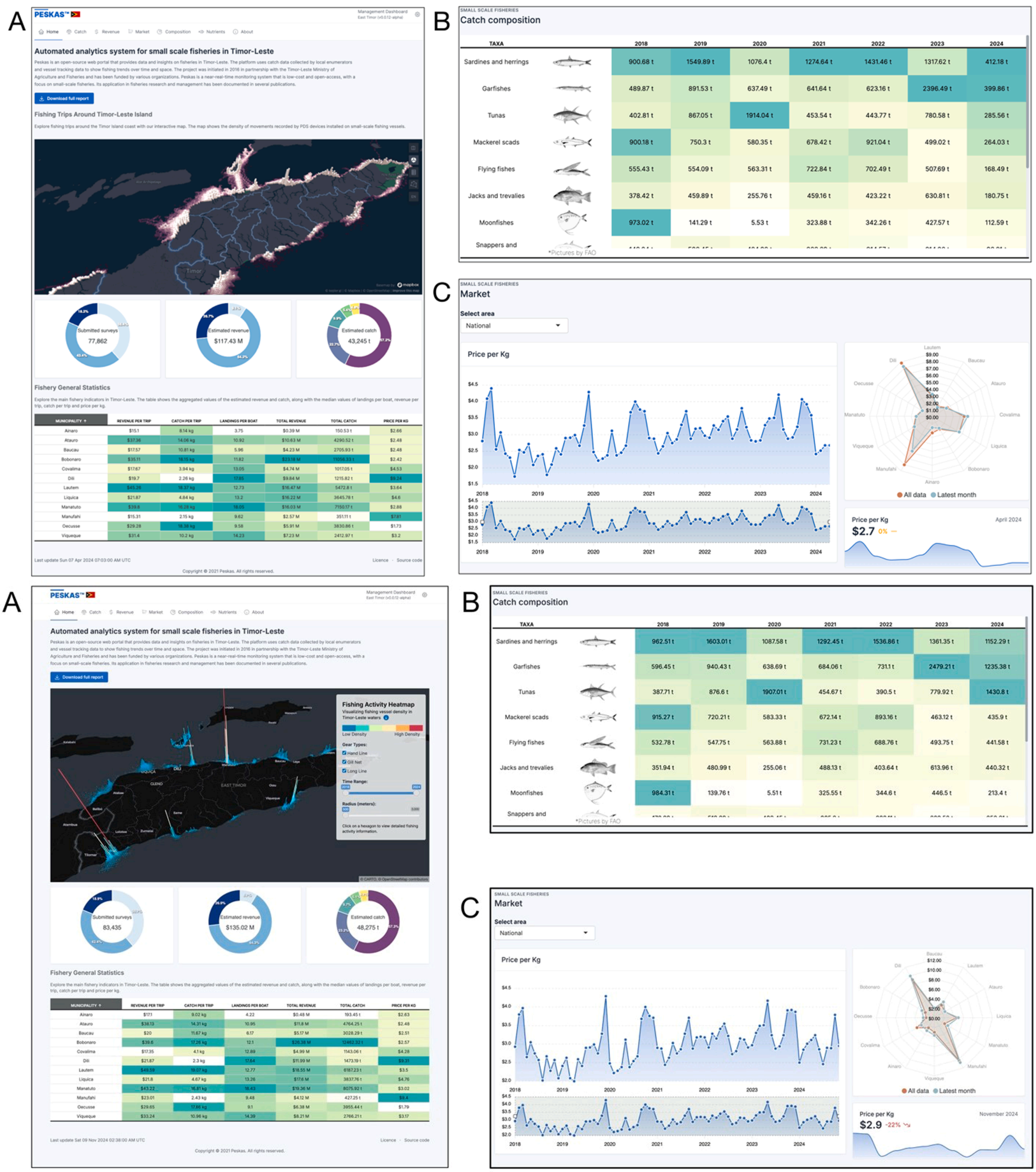

Fig. 3. Illustrative elements of Peskas' interactive dashboard of Timor-Leste small-scale fisheries. Panel A Homepage of the dashboard featuring navigation tabs, portal settings, and an interactive map generated with kepler.gl visualising the distribution of fishing boat tracks. It also showcases interactive charts and tables that aggregate revenue and catch estimates at national and municipal levels. Panel B. An interactive and sortable table detailing the aggregated annual catch in tons for key fish-group stocks, along with visual representations for each species. Panel C. Multifaceted time-series analysis tool that displays market trends (also available for catch and revenue), including a detailed and customizable graph on price per kilogram fluctuations over time and a radar chart comparing monthly catch volumes.

Furthermore, Peskas was used to highlight the impact of COVID-19 on fisheries value chains and subsistence in the Timor-Leste context [21] with which to plan COVID responses and interventions in coastal communities.

Specific research has highlighted priority areas and gaps in management capacity, errors in scientific knowledge [24] and development needs [25]. It has enabled the rigorous testing of fisheries technology like nearshore Fish Aggregating Devices (FADs) to inform government investment schemes and support for coastal fisheries. These are objects moored in coastal waters to attract fish and provide small-scale fishers access to a new and more sustainable source of fish, without requiring investment (or subsidies) for new equipment, fuel or techniques [26]. The analysis of habitat-specific catch rates (including FADs) demonstrated that social and ecological factors affect the rate of return on investment (costs of FAD equipment, deployment and maintenance), but that FADs have great potential as climate-smart technologies to enhance food security while improving environmental sustainability [27].

The aim of the government to decentralise fisheries management to municipal and local stakeholders [28] is slowed by broader infrastructure and institutional capacity issues, but co-management, where the various stakeholders come together to design mutual goals and management mechanisms [29], has shown promise in Timor-Leste. Peskas was utilised in this case to illustrate how coastal fisheries and fishing patterns differ by location and dissuade the one-size fits-all approach [30].

Peskas championed the sex disaggregation of fisheries data to understand the roles of women in Timor-Leste fisheries, and their contributions to household food and nutrition security [31,32]. This has identified and prioritised data gaps, and has been leveraged to highlight and challenge gender and social norms in Timor-Leste [31] which is crucial for inclusive management practices.

The nutritional and developmental benefits of consuming fish are becoming increasingly clear, especially in lactating mothers and young children [6,33,34]. However, in Timor-Leste, where rates of child stunting malnutrition are the highest in the world [35], fish consumption in upland, inland areas are typically very low and approximately a quarter of consumption rates in coastal areas [36]. A randomised controlled trial has leveraged Peskas ongoing monitoring of catch rates and fishing revenue as part of a clinical trial in Timor-Leste to test the effects of increasing supply (FADs) and demand (behaviour change messaging) on the consumption of fish products in inland and upland communities [37]. A nascent research direction related to this, is the integration of nutrition-sensitive fisheries management approaches into Peskas, where the catches from different fishing patterns (gear, location, habitat) exhibit common nutrient concentration profiles, which can be utilised for management strategies that do not solely maximise production, but also address nutritional needs in the population [38].

Peskas has changed the daily practice of key stakeholders, enabling new interactions between fishers, community enumerators, NGOs, and government officials [39]. While concrete policy change is slowed by weak legal infrastructure and institutional capacity, Peskas is an enabler of co-management processes, by providing the platform of transparent, trustworthy data for improved collaboration and communication. A study that evaluated the impact of Peskas on fisheries management objectives found that despite limited regulatory changes, Peskas had brought about significant national and international investment into the fisheries sector, had driven improved collaboration between government departments, as well as vertical communication channels from coastal fishing communities to national government officers [39]. Timor-Leste has one of the fastest growing populations in the world, so there are lots of young, digitally capable people leaving school and searching for meaningful work, and one impact from Peskas is the creation of new enumerator positions in each municipality, bringing much needed income into rural economies [39]. The impacts observed and stated by stakeholders around collaboration, transparency and communication [39] have spawned the development of new research questions related to the role of digital transformation on behaviour and preference in fisheries management and conservation. Currently in preparation is a protocol to test the effects of access to Peskas information at different resolutions on the perceptions and preferences of fisheries stakeholders in southern Kenya.

As more locations and fisheries are added to the platform, the approach to data privacy will become increasingly important to standardise. At present, the data are published online with the permission of governments and adhere to national privacy regulations. As Peskas decentralises further and allows for cooperative and individual fisher data reporting, analysis and management, permissions will be sought at each of those levels accordingly. The crucial challenge moving forward is to ensure that Peskas develops with a strong emphasis on inclusion, prioritising access to technology and approaches that narrow the digital divide facing the small-scale fisheries sector [40].

Sustainability and scaling

Peskas was developed iteratively over 3 years under the WorldFish donor-funded Fisheries Sector Support Program. The sustainability strategy of Peskas is based on government and stakeholders assuming responsibility and costs of data collection (enumerator salaries and validation responsibilities) and contributing to the cost of maintaining the software and platform. Maintaining and updating the code of Peskas involves periodic updates to the software, data validation workflows, and training for new users. Automated workflows and cloud-based infrastructure, such as GitHub Actions and Google Cloud services ensure that long-term maintenance costs remain low. In 2019, the Timor-Leste Fisheries Directorate formally adopted Peskas as their national monitoring system and invested in new enumerators for every coastal municipality [41]. This uptake effectively brought the ∼16,000 km^2 of Timor-Leste's marine territory under improved, evidence-based management [42].

Being modular and code-based, Peskas is highly adaptable and scalable. It is not designed to be an off-the-shelf, turnkey solution but the existing structure can be used as such if no fisheries monitoring, or information systems are in place. Peskas allows for the customisation of some or all modules to different contexts and countries. This contextualisation, such as building catch surveys to reflect local fisheries characteristics, conditions, methods, target species and regulations for example, involves discussion and collaboration with local stakeholders and experts. Peskas was co-designed around enumerators collecting data at landing sites, but data can be obtained from adequately trained and engaged fishers – and work is underway to design and deploy a fisher app that would allow fishers to collect and use their own data for decision-making. The Peskas dashboard has had ∼1400 visitors from 86 countries and has been cited in 31 publications since 2020. Currently Peskas modules are being adapted to the aquaculture sector in Timor-Leste, and scaled to East and Southern Africa in collaboration with government agencies and NGO partners in Kenya, Zanzibar, Mozambique and Malawi [43].

Clearly the software development and management aspects of the Peskas monitoring system are not easily assumed by host countries, so the long-term goal of this system is to provide a publicly accessible platform through which users can visualise, analyse and manage anonymised small-scale fisheries information according to their roles, from fishers, to researchers, to managers. The goal of Peskas is to provide greater transparency of information about small-scale fisheries to enhance equitable governance of aquatic food systems that sustain livelihoods, food security, and biodiversity.

The costliest element of the Peskas ecosystem is the vessel tracking, as this involves hardware purchase and a replacement plan, and ongoing data fees. Vessel tracking is not a compulsory module of Peskas, and to minimise ongoing costs can be removed or reduced to only when needed to answer specific research questions related to fisheries behaviour, compliance, and effort. However, behaviour of industrial fisheries are becoming more transparent thanks to platforms like Global Fishing Watch that makes some industrial fishing vessel movement data publicly available from Automatic Identification Systems and Vessel Monitoring Systems [44]. Small-scale fisheries are data-deficient almost everywhere they are found, especially in low- and middle-income countries where they are often an informal economy and highly diverse and geographically remote [1,4,45]. The absence of SSF vessel movement data prevents their full participation in international trade and hinders their contribution to ocean transparency [46]. This gap also complicates efforts to develop equitable ocean governance, as dialogues and decisions fail to incorporate the behaviours, dynamics, and needs of small-scale fishers [47,48] or exclude them from trade opportunities through costly reporting requirements for traceability [49,50].

A specific indicator (14.7.1) of the sustainable development goals is "Sustainable fisheries as a percentage of Gross Domestic Product in […] all countries". Until now, mechanisms to measure this contribution effectively, in real time for SSF have not existed. Peskas brings rigorous, quantitative data from small-scale fisheries into ocean accounting for the first time, empowering small-scale fishers with 'a seat at the table' in blue economy dialogues and negotiations and enabling integration of SSF into national food balance sheets and sustainable development goals.

4. Conclusions

Peskas as an open-source solution to facilitate and support adaptation and collaboration is the first of its kind and represents a purposeful proposition for sustainable digital transformation in one of the world's poorest contexts. Too often low-income country communities are the testing ground for new technologies, but which inevitably fail due to lack of contextualisation with end users, or unreasonable cost-recovery expectations. The Peskas code and workflow are free to use and adapt, and we believe can be the basis for a sustainable mechanism from which to build digital transformation not just in fisheries, but across small-scale production sectors. While the collection of data is certainly not free, most governments already invest in monitoring of some kind, but these are often paper based, labour intensive and manually analysed, and the data are stored in excel or outdated databases that are difficult to adapt or extract. With some small adjustments, existing monitoring procedures can feed data into Peskas, from where it will be trustworthy, secure, transparent and available for decisions. From here the emphasis must be to continue to build the capacity to collect good data, develop and adapt the systems, to analyse and understand the data in social-ecological terms, and use the knowledge to make smart decisions based on management target reference points and scientifically evidenced thresholds.

CRediT authorship contribution statement

Lorenzo Longobardi: Writing – original draft, Software, Methodology, Data curation. **Villiam Sozinho:** Resources, Data curation. **Hamza Altarturi:** Writing – review & editing, Validation. **E. Fernando Cagua:** Validation, Software, Resources. **Alexander Tilley:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors have no conflicts of interest to declare.

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