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'InfraRivChange': a web application to monitor river migration at sites of critical bridge infrastructure in the Philippines

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ABSTRACT
Shifting rivers, particularly with high migration rates, represent a geomorphic hazard at sites of critical bridge infrastructure. Conventional attempts to map and measure shifts in the position of river channels usually requires the manual digitization of riverbanks from satellite imagery using Geographic Information Systems (GIS) – a time-consuming process only feasible at a limited number of bridge sites using a small selection of satellite images. As part of the CDRI Fellowship, the authors leveraged the cloud computing platform Google Earth Engine (GEE) to substantially upscale analyses using Earth observation (EO) data. Focusing on the Philippines, they designed a user-friendly web application for technical and non-technical users to monitor the relative risk of river migration at sites of critical bridge infrastructure by analysing thousands of satellite images. 'InfraRivChange' uses openly accessible satellite imagery from Landsat (30 m spatial resolution) and Sentinel (10 m spatial resolution) to quantify river channel changes at bridge sites. The study demonstrates the web application at test sites and suggests use-cases relevant to disaster resilient infrastructure. As a low-cost approach for monitoring shifting large rivers in the vicinity of infrastructure, InfraRivChange can be incorporated into bridge monitoring systems (e.g., as a component of bridge stability assessments) and inform the design and placement of future infrastructure. They envision that InfraRivChange can be applied to additional forms transport infrastructure adjacent to rivers (e.g., road and rail) and extended to other dynamic riverine settings.

KEYWORDS
Critical bridge infrastructure; transportation; geomorphic hazards; river hazards; satellite imagery

1. Introduction

The Philippines is among the most vulnerable countries in Southeast Asia exposed to the impacts of climate change (Yusuf & Francisco, 2009) and consistently ranks as one of the countries most affected by extreme weather globally (Eckstein, Künzel & Schäfer, 2021). Climate change is impacting the magnitude and frequency of extreme flood-generating storms (Eccles, Zhang & Hamilton, 2019; Tolentino et al., 2016) and a high proportion of the population are exposed to hazards arising from fluvial flooding and erosion (Smith et al., 2019). Hydrometeorological hazards such as floods and rainfall-triggered landslides (Abancó et al., 2021; Catane et al., 2012) damage critical infrastructure, especially transport infrastructure like bridges, roads and railways.

River bridges are vulnerable nodes in transport and utility networks, and are more exposed to hydrometeorological hazards than other infrastructure assets (Pregnolato, 2019). Their damages or destruction result in high socio-economic costs (Enke et al., 2008). River migration and associated scour represents a systemic hazard at sites of critical bridge infrastructure. In the Philippines, where exposure to flooding and geomorphic risks are considerable (Dingle et al., 2019), recent expansion of infrastructure developments (World Bank, 2018) warrants quantification of river migration in the vicinities of large bridge assets. Road networks in the Philippines handle 90% of passenger and 50% of freight transportation (Vallejo, 2015) and are vital for linking rural communities (Olsson, 2009), but considerable damages are recorded during hydrometeorological events. As climate change increases the frequency and magnitude of typhoons and storms in tropical regions, it will further undermine the stability of bridges, levees and other infrastructure (Eccles, Zhang & Hamilton, 2019).

To address river migration in relation to transport infrastructure, Earth observation (EO) data can be used to monitor river channel change in the vicinity of bridges. This information can improve understanding of river behaviour and help in the design of mitigation measures for transport infrastructure. Capturing satellite imagery at predictable time intervals is a major advantage for mapping changes in river channels (Carbonneau & Piégay, 2012), and for very large river systems, aerial or satellite remote sensing systems can be the only way to observe and quantify planimetric morphology (Gilvear & Bryant, 2016). Hazard monitoring from satellite imagery has been completed around large

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bridges on the Padma River, Bangladesh (McLean et al., 2012) and Ayeyarwady River, Myanmar (Oo, Kyi & Zin, 2019). Although EO data supports a range of disaster risk reduction activities, the large volumes of data available to risk practitioners can be challenging to handle and process.

Technological advances in digital infrastructure, increased computing power and data storage capabilities have given rise to cloud computing platforms, providing on-demand access to high-performance computing facilities without a need to own and maintain physical hardware (Sudmanns et al., 2020). An example is Google Earth Engine (GEE), a cloud computing platform for planetary-scale geospatial analysis (Gorelick et al., 2017). GEE holds a substantial data catalogue of EO data, providing near real-time access to satellite imagery over long durations. As part of the CDRI Fellowship we developed a bespoke web application using GEE for monitoring shifting rivers in the vicinity of critical bridge infrastructure.

This conference paper introduces the newly developed web application InfraRivChange. We detail the satellite imagery analysis workflow, demonstrate three test cases from the Philippines and showcase transferability to other dynamic riverine settings using an example from India.

2. Methods

We apply the multitemporal satellite imagery analysis approach developed by Boothroyd et al. (2021) through a custom-built GEE web application. Here, we summarize the methodology including satellite imagery analyses and design of the GEE web application (Figure 1).

2.1. Satellite imagery analyses

Primary data sources are shown in Table 1; they include Landsat products (30 m spatial resolution; available for 1984-present) and Sentinel collections (10 m spatial resolution; available for 2015-present). Multitemporal, multispectral satellite observations from the Landsat program and Sentinel constellation are particularly useful for disaster resilience applications with archives of data that span almost four decades. We use surface reflectance products from Landsat; the images have been atmospherically corrected, facilitating a more reliable comparison of spectral reflectance measurements between acquisitions. For Sentinel imagery, we use Level 1C products to maximize the record length of imagery.

Abbreviations: ETM-enhanced thematic mapper; MSI-multispectral instrument; OLI-operational land imager; TIRS-thermal infrared sensor; TM-thematic mapper.

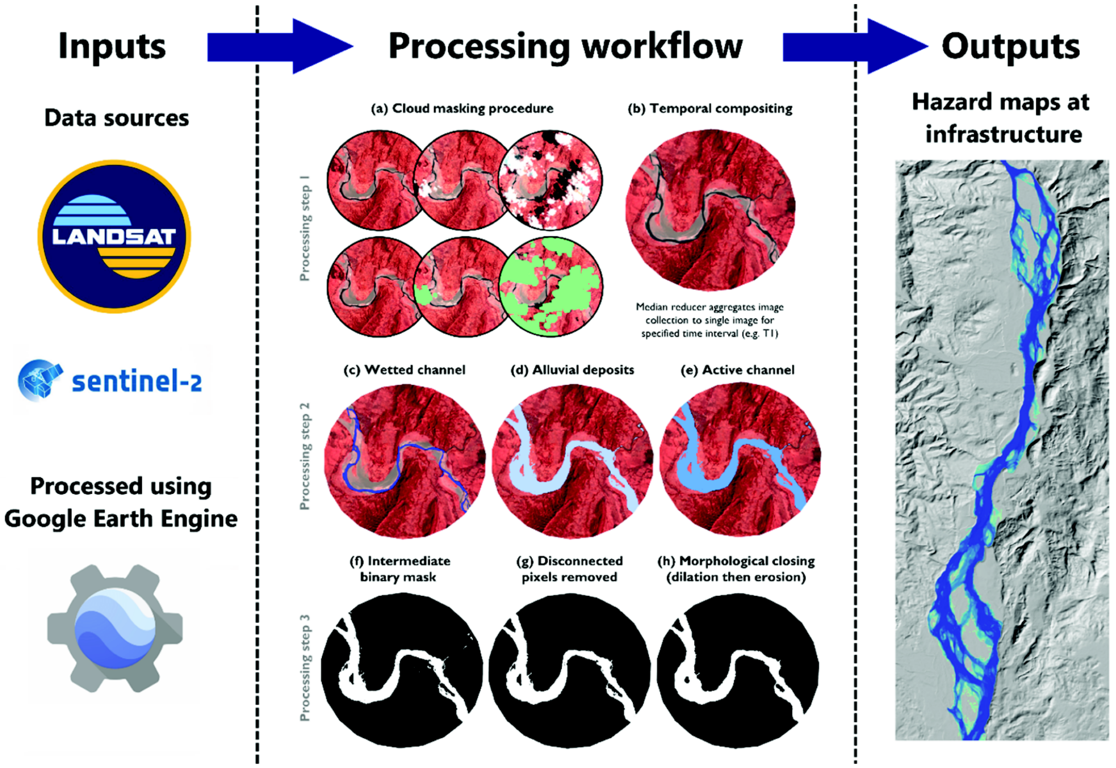


Figure 1. Conceptualization of the research methodology, including the data sources (Landsat and Sentinel imagery), processing steps within GEE and the outputs to be used by stakeholders.

Table 1. Characteristics of the satellite imagery data used in InfraRivChange.

Data Set	Spatial Resolution	Temporal Revisit	Temporal Archive	Dataset in GEE Catalogue
Landsat 5 TM	30 m	16 days	1984–2012	Landsat 5
Landsat 7 ETM +	30 m	16 days	1999–present	Landsat 7
Landsat 8 OLI/TIRS	30 m	16 days	2013–present	Landsat 8
Sentinel-2 MSI	10 m	10 days	2015–present	Sentinel-2

A key feature of Landsat and Sentinel data is the availability of multispectral bands, e.g., near-infrared and short-wave infrared. Spectral bands can be combined to calculate multispectral indices, useful for indicating the relative abundance of features of interest such as vegetation and water.

We apply the processing workflow developed by Boothroyd et al. (2021) to classify the active channel from satellite imagery for different time periods and assess shifts in river channel position. The workflow has three main processing steps: (i) cloud masking and temporal compositing; (ii) active river channel classification; and (iii) binary image cleaning. Validation work has been published previously to assess the accuracy of the active river channel classification (Boothroyd et al., 2021). We use similarity coefficients to interpret relative risks of shifting rivers to critical bridge infrastructure based on binary image outputs from the workflow. Differences are identified using the Jaccard index and Dice similarity coefficient. Values closer to 1 indicate greater similarity between active river channel masks, implying that positional shifts in the active river channel were negligible. In addition to similarity coefficients, we also report areal statistics for each of the binary images. We report the number of active channel pixels within the region of interest and the area of the active channel (km^2) for each time period of analysis. Changes in the active channel area and similarity coefficients indicate potential threats to critical bridge infrastructure.

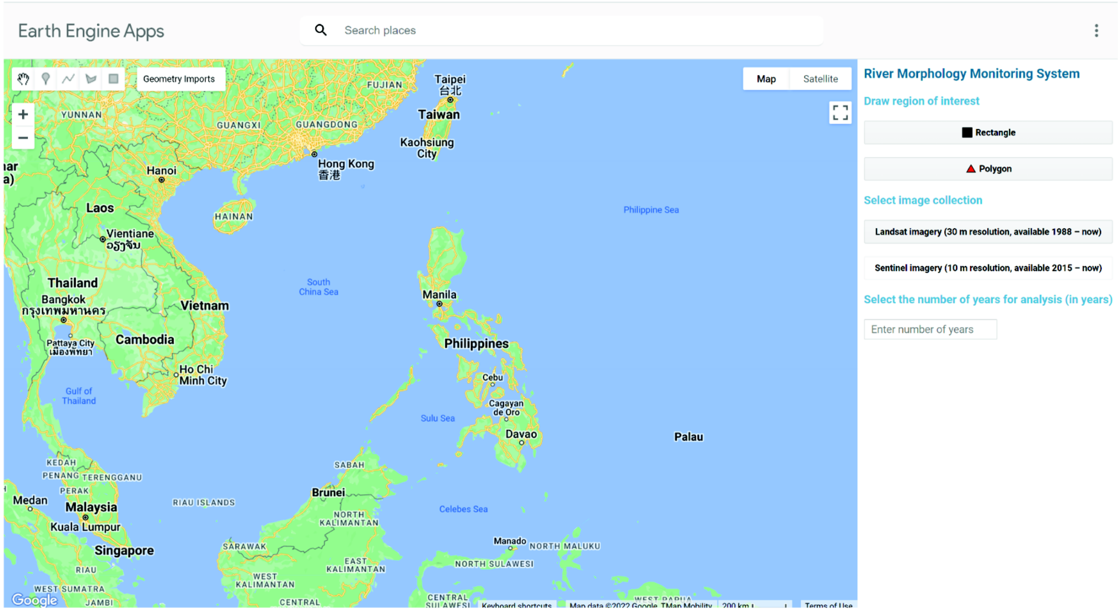
2.2. *Web application design*

We designed a web application (Figure 2) to allow technical and non-technical users to apply the satellite imagery workflow (available online: https://vrindasharma.users.earthengine.app/view/infrariv; and accessible via any web browser, even without a Google account).

3. Results

3.1. *InfraRivChange demonstration using Landsat imagery*

In the first test case we demonstrate results from the Landsat imagery workflow for the Gamu Bridge on the Cagayan River (Figure 3). Using default input



River Morphology Monitoring System

Draw region of interest

Rectangle

Polygon

Select image collection

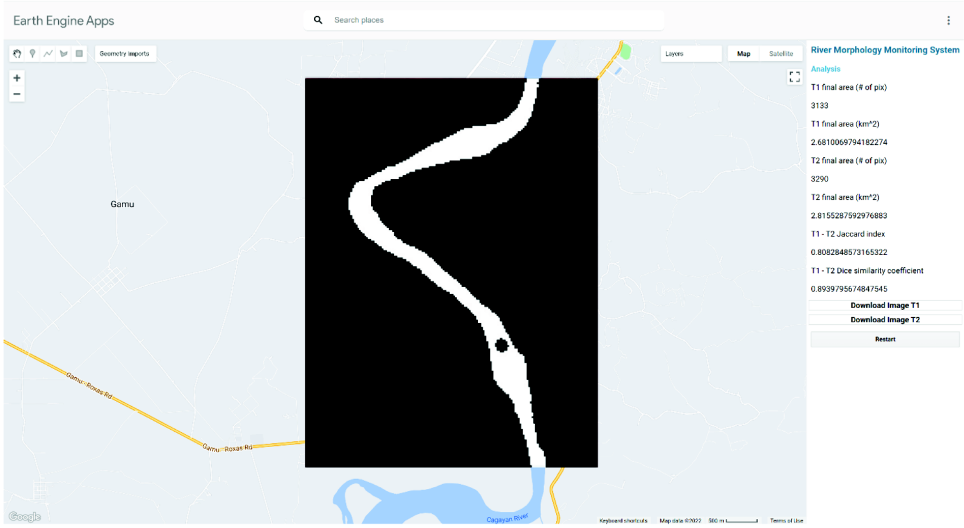
Landsat imagery (30 m resolution, available 1988 – now)

Sentinel imagery (10 m resolution, available 2015 – now)

Select the number of years for analysis (in years)

Enter number of years

Figure 2. Landing page of the InfraRivChange web application.



River Morphology Monitoring System

Analysis

T1 final area (# of pix)

3133

T1 final area (km^2)

2.6810069794182274

T2 final area (# of pix)

3290

T2 final area (km^2)

2.8155287592976883

T1 - T2 Jaccard index

0.8082848573165322

T1 - T2 Dice similarity coefficient

0.8939795674847545

Figure 3. Landsat example from the Gamu Bridge; Cagayan River.

parameters, we set the date range as T1 = 01/01/1988 – 01/01/1990 and T2 = 01/01/2018 – 01/01/2020. Results indicate that the section of the Cagayan River has remained approximately stable over the 30-year analysis period. The active channel area has increased marginally (from 2.68 to 2.82 km^2), with the Jaccard index (0.81) and Dice similarity coefficient (0.89) indicating a low relative risk to critical bridge infrastructure. Results from InfraRivChange suggest only minor shifts in the active river channel position at this site.

In the second test case we demonstrate results from the Landsat imagery workflow for the Itawes Bridge on the Chico River (Figure 4). Using default input parameters, we set the date range as T1 = 01/01/1988 – 01/01/1990 and T2 = 01/01/2018 – 01/01/2020. Notable here is the mobility of the Chico River in the vicinity of the bridge site over the 30-year analysis period. The active channel area has increased marginally (from 1.41 km^2 to 1.50 km^2), with the Jaccard index (0.53) and Dice similarity coefficient (0.69) indicating a moderate relative risk to critical bridge infrastructure. Results from InfraRivChange suggest moderate shifts in the active river channel position at this site, indicating the need for further investigation and potentially applying more detailed bridge monitoring.

River Morphology Monitoring System

Analysis

T1 final area (# of pix)

1655

T1 final area (km^2)

1.4090406253535221

T2 final area (# of pix)

1758

T2 final area (km^2)

1.5030882894526436

T1 - T2 Jaccard index

0.5310167166692379

T1 - T2 Dice similarity coefficient

0.6936785351690699

Figure 4. Landsat example from the Itawes Bridge; Chico River.

3.2. InfraRivChange demonstration using Sentinel imagery

In the third test case we demonstrate results from the Sentinel imagery workflow for the Don Mariano Marcos Bridge on the Lagben River (Figure 5). Using default input parameters, we set the date range as T1 = 01/01/2016 – 01/01/2017 and T2 = 01/01/2021 – 01/01/2022. Results indicate that the section of the Lagben River has remained approximately stable over the five-year analysis period. The active channel area has decreased marginally (from 2.12 km^2 to 1.94 km^2), with the Jaccard index (0.83) and Dice similarity coefficient (0.91) indicating a low relative risk to critical bridge infrastructure. Results from InfraRivChange suggest only minor shifts in the active river channel position at this site. However, it is important to note that these changes have occurred over a relatively short timescale (five years, relative to the 30-year timescale of the Landsat workflow).

4. Discussion

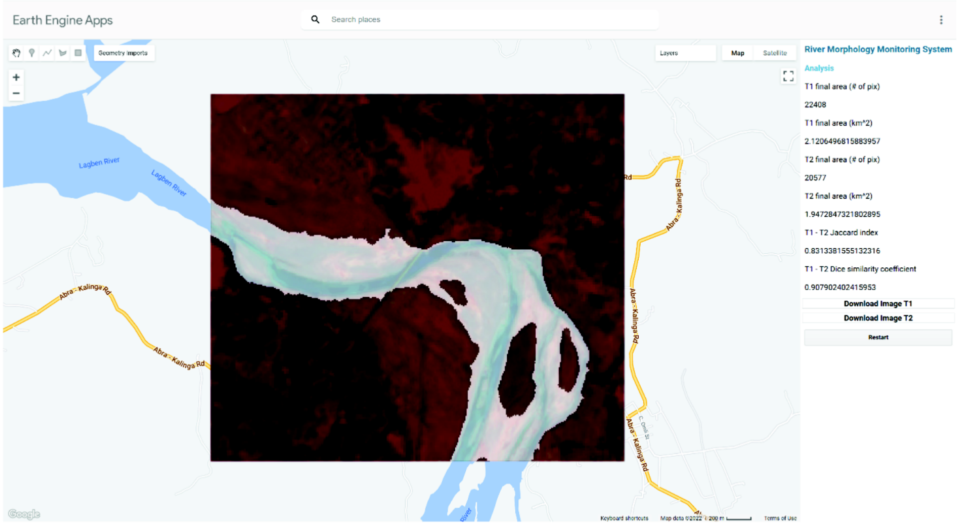
Satellite imagery analyses offer a low-cost approach for monitoring the relative risk of shifting rivers (> 100 m in width) to critical bridge infrastructure. We propose that satellite imagery analyses can be formally incorporated into bridge monitoring investigations (e.g., as a component of bridge stability assessments) undertaken by primary stakeholders to inform the design and strategic placement of future bridge infrastructure. It has potential for other forms of critical infrastructure adjacent to rivers such as road and rail.

It is important to sense-check outputs from InfraRivChange. Although best efforts have been made to validate and calibrate parameter sets for rivers in the Philippines, all outputs should be sense-checked and critically appraised for other sites. In terms of default values, for Landsat applications we recommend NDVI = 0.2, MNDWI = −0.4 and binary cleaning pixels = 100. For Sentinel applications we recommend NDVI = 0.2, MNDWI = −0.175 and binary cleaning pixels = 300. Individual applications may require customization of default values to improve the classification of the active river channel.

Transferability is used as a term to describe how information or analysis from one region can be applied elsewhere to achieve universality of the approach. The web application can be easily transferred to other dynamic riverine settings where critical bridge infrastructure is at risk from shifting rivers across Southeast Asia. In future, the application may be further developed, validated, calibrated and applied across a geodiverse range of settings. Figure 6 shows an additional example for the Ghaghara River (India) between 1990 and 2020, with the Chahlari Ghat Bridge located at the centre of the image. The Jaccard index (0.15) and Dice similarity coefficient (0.26) are very low, indicating considerable shifts in active channel position. The example demonstrates the potential of transferring the workflow from the Philippines to other dynamic riverine settings.

5. Conclusions

We developed a web application to monitor shifting rivers in the vicinity of critical bridge infrastructure in the Philippines. InfraRivChange has been designed to offer non-technical and technical users the opportunity



River Morphology Monitoring System

Analysis

T1 final area (# of pix)

22408

T1 final area (km^2)

2.1206496815883957

T2 final area (# of pix)

20577

T2 final area (km^2)

1.9472847321802895

T1 - T2 Jaccard index

0.8313381555132316

T1 - T2 Dice similarity coefficient

0.907902402415953

Figure 5. Sentinel example from the Don Mariano Marcos Bridge; Lagben River.

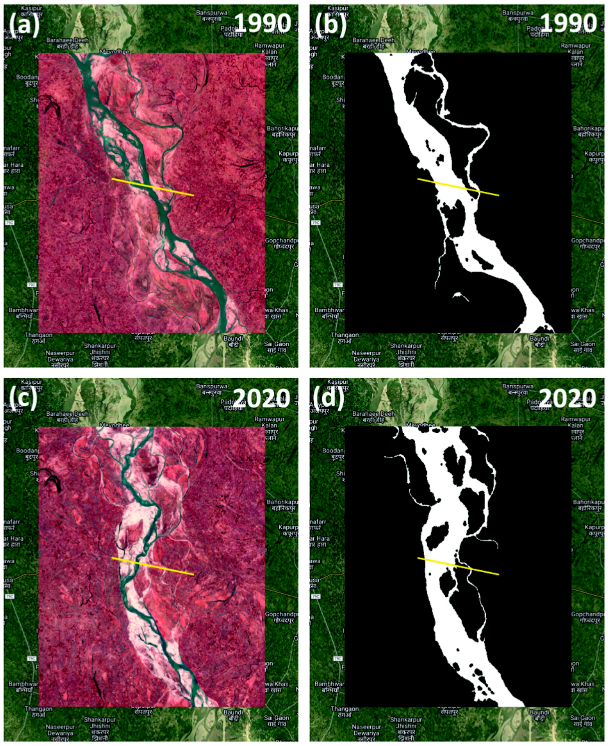


Figure 6. InfraRivChange web application applied outside of the Philippines, to the Chahlari Ghat Bridge (*India*).

to apply advanced satellite imagery workflows to thousands of Landsat and Sentinel images. The user-friendly web application enables semi-automated multitemporal satellite imagery analyses to be undertaken. Outputs can be used by stakeholders to assess the relative risk of river migration at sites of critical bridge infrastructure. We recommend that InfraRivChange can be used as a low-cost remote sensing approach to monitor shifting rivers at sites of critical bridge infrastructure. Satellite imagery analyses could be formally incorporated into bridge monitoring investigations (e.g., as a component of bridge stability assessments) and inform the design and placement of future infrastructure. We envision that InfraRivChange can be applied to other critical infrastructure adjacent to rivers (e.g., road, rail and pipelines) and extended elsewhere to other dynamic riverine settings.

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Disclosure statement

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