

iHVI: AN OPEN-SOURCE TOOLKIT FOR CONSTRUCTING INTEGRATED HEAT VULNERABILITY INDEX IN AUSTRALIA

Q.(C.) Sun^{1*}, S. Das¹, K. Wang¹, Y. Tao¹, M. Amati², J. Hurley², S. Choy¹, M. Duckham¹

¹ Geospatial Science, School of Science, RMIT University, Australia – (chayn.sun, shinjita.das, kaige.wang, yaguang.tao, suelynn.choy, matt.duckham)@rmit.edu.au

² Global, Urban and Social Studies, RMIT University, Australia – (marco.amati, joe.hurley)@rmit.edu.au

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ABSTRACT:

To tackle the increasing issue of heat risk in Australia and pressure of population growth, this project aimed to establish a first nationwide dynamic and interactive heat vulnerability assessment toolkit. The toolkit integrated multiple data sources, cloud computing, and Web GIS technologies to deliver cool intelligence for more heat resilient Australian cities and suburbs. A cloud-based open-source tool, iGEE, was first developed to derive land surface temperature (LST), NDBI (normalized difference built-up index) and NDVI (normalized difference vegetation index) from multiple satellite imagery on Google Earth Engine (GEE), a no-code web application allowing users to retrieve satellite data for a large area at fine scales. Following that, a python-based desktop app was then developed to calculate an integrated Heat Vulnerability Index (iHVI) for any cities and area at a fine scale of Statistical Area 1 (SA1). The iHVI toolkit allows users to construct heat sensitivity, heat adaptive capability indicators, and composite heat vulnerability index, which enables modelling of the relationships between heat, environmental and socioeconomic factors.

1. INTRODUCTION

1.1 Aim and Objectives

Mapping and analysing land surface temperature and landcover changes helps us to understand the relationship between urbanisation and the urban heat island effect (Das, Sun, & Zhou, 2022; Duncan et al., 2019; Rakoto, Deilami, Hurley, Amati, & Sun, 2021). There is an increasing demand in heat vulnerability assessment to identify areas that are vulnerable to heat waves, and takes into account the location of vulnerable members of the community, such as the elderly, very young and those with lower capacity to adapt to heat (Q. C. Sun et al., 2021). This Australian Urban Research Infrastructure Network (AURIN) funded project aimed to establish a first nationwide dynamic and interactive heat vulnerability assessment toolkit. The toolkit integrated multiple data sources and GIS technologies to deliver cool intelligence for more heat resilient Australian cities and suburbs. The iHVI toolkit also constructs heat sensitivity, heat adaptive capability indicators, and composite heat vulnerability index. The objectives are to:

1. Develop tools to derive land surface temperature (LST) and classify landcover types (NDBI and NDVI) via Google Earth Engine (GEE) API.
2. Develop tools to construct heat sensitivity, heat adaptive capability indicators and composite heat vulnerability index.
3. Enable modelling of the relationships between heat, environmental and social-economic factors.

1.2 HVI Conceptual Framework

Figure 1 (page 5) shows the conceptual heat vulnerability assessment framework. It is a four-stage assessment framework to derive heat vulnerability index by calculating heat exposure

index, heat sensitivity index and adaptive capability index for intervention strategies.

The first stage is to define the key variables/ indicators obtained from multiple sources. Two databases were created to store environmental and socio-economic indicators. Under environmental indicator, mean land surface temperature and land cover data (NDVI and NDBI) for SA1s were downloaded from the iGEE web tool (www.gisonmeta.com) in CSV format. Population and socio-economic census indicators were downloaded from the Australian Bureau of Statistics for SA1s in CSV format.

Index	Indicators	Justifications
Heat Exposure	A: Mean Land surface temperature	Provides an exposure indicator of urban heat island effect and heat vulnerability.
Heat Sensitivity	B: Mean NDBI (normalized difference built-up index)	Provides a sensitivity indicator for the retention of heat in an urban environment. Quantifies the mean value of the built-up area and impervious surfaces in an urban area.
	C: Mean NDVI (normalized difference vegetation index)	Provides a sensitivity indicator for the retention of heat in an urban environment. Quantifies the mean value of the vegetation cover in an urban area.
	D: Population density	Prevents the generation of spatial biases induced by very large/small census tracts. High number corresponding with a high sensitivity score, as denser of population are more sensitive to health complications.
	E: % of aged 65+	with high number corresponding with a high sensitivity score, as elderly people are more sensitive to heat related health complications.
	F: % of aged 4-	with high number corresponding with a high sensitivity score, as school kids are more sensitive to heat related health complications.
	G: % of population need care	with high number corresponding with a high sensitivity score, as more persons needing care indicating more sensitive to heat related health complications.
Adaptive capability	H: Education level	as populations with higher education are more accessible for resources to respond to heat.
	I: Income level	as populations with higher income are more accessible for resources to respond to heat.

Table 1: iHVI index, indicators, and justifications.

* Corresponding author

Table 1 summarises the environmental and socio-economic indicators used in the toolkit (Q. Sun et al., 2019). The original values of the indicators were normalised between 0 and 1 using min-max normalisation, so that the normalised values of each indicator are relative importance measures of each SA1s in relation to the others.

The second stage is to compute the heat vulnerability indexes using normalised indicators. The first index is the ‘heat exposure index’, which is calculated from the ‘Mean Land surface temperature’ indicator. The second is ‘Heat Sensitivity index’ which is based on six indicators, i.e., NDBI, NDVI, Population density, % of aged 65+, % of aged 4- and % of population need care. The third index is called ‘Adaptive capability index’ which includes education level and income level indicators. The third and forth stage of iHVI calculation are to integrate the three components and compute a final composite HVI using quintile methods (see section 2.2).

2. TOOLKIT DEVELOPMENT

2.1 iGEE Web Tool

A cloud-based open-source GIS application, iGEE, was first developed for the iHVI toolkit as a web tool to bridge the gap between GIS and other users by demonstrating the ability of cloud mapping on Google Earth Engine and enabling deriving indicators without coding. GEE is cloud platform which combines a multi-petabyte catalog of satellite imagery and geospatial datasets with planetary-scale analysis capabilities and makes it available for users to detect changes, map trends, and quantify differences on the Earth's surface (Gorelick et al., 2017). It is especially beneficial for urban researchers to derive time series data for urban informatics. However, processing on GEE requires coding capability, such as JavaScript and Python programming. The iGEE web tool has overcome this barrier to call GEE API and parameterize the codes into clickable buttons for researchers without programming skills (Tamiminia et al., 2020).

Datasets	Spatial resolution (m)	Time period	Satellite image
LST- Landsat	30	2013-04-11- present	USGS Landsat 8 Surface Reflectance Tier 1
LST- MODIS	1000	2002-07-04- present	MYD11A2.006 Aqua Land Surface Temperature and Emissivity 8-Day Global 1km
NDBI	10	2015-06-23 - present	Sentinel-2MSI: Multispectral Instrument, Level-1C
NDVI	10	2015-06-23 - present	Sentinel-2MSI: Multispectral Instrument, Level-1C

Table 2. LST and Landcover datasets description and formats.

The iGEE web tool uses Landsat 8, Sentinel-2, and MODIS satellite data to derive LST and Landcover parameters, as shown in Table 2. Land surface temperature (LST) data was retrieved using Landsat 8 Surface Reflectance satellite and MODIS Aqua Land Surface Temperature and Emissivity satellite. To retrieve landcover parameters (NDVI and NDBI), the Sentinel-2 satellite imagery was used. Statistical Area Level 1s (SA1) shapefile polygon was imported from the Australian Bureau of Statistics (ABS) to attribute the mean value of the parameters to a fine-scale local level area. It was imported as Earth Engine cloud assets.

The iGEE web tool is directly built on the Google Earth Engine (GEE) platform. The web tool uses the GEE client library (JavaScript) and EO satellites from the GEE data catalog to operate. The tool contains data processing and exporting GEE libraries built using JavaScript in the GEE code editor. The library uses different functions to retrieve, process and export nationwide land surface temperature and land cover datasets for Australia. Figure 1 shows the code editor interface that compiles JavaScript codes to retrieve, process and export the land surface temperature and landcover parameters using Earth Observation (EO) satellites.

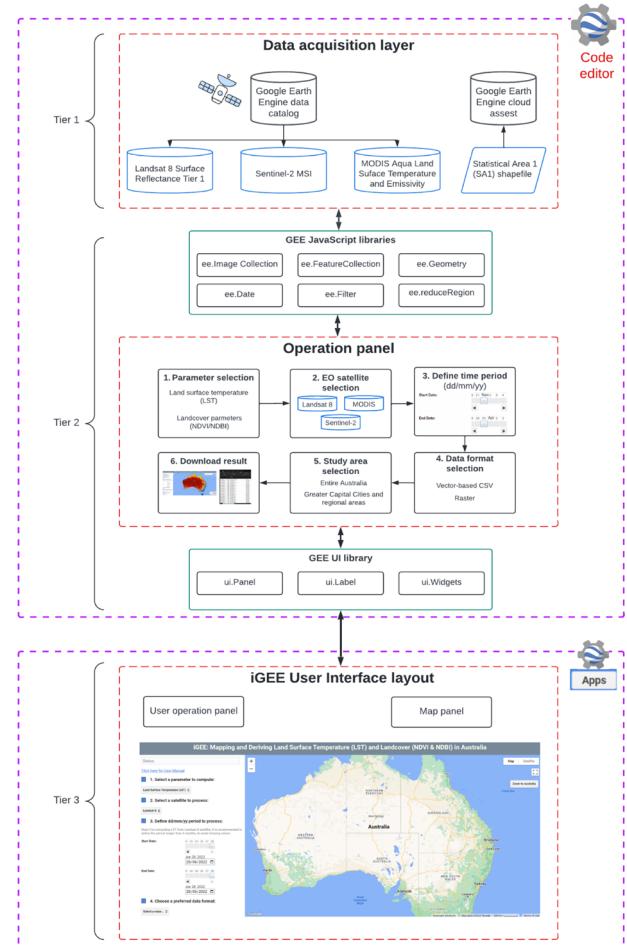


Figure 2. iGEE web tool architecture.

Figure 2 illustrates the three-tier architecture of the proposed web tool. The first tier represents the ‘data acquisition layer’ which accesses the satellite from the GEE catalog and stores the imported SA1 data under GEE cloud assets. The second tier is called the ‘operation layer’, which serves as a logic tier of the web tool. It uses GEE JavaScript libraries to connect the ‘data acquisition layer’ to leverage Landsat, Sentinel and MODIS EO

satellite imageries to calculate and export Land Surface Temperature (LST) and Landcover (NDVI & NDBI) parameters for Australia. The third tier represents the ‘iGEE user interface’, which contains the user operation panel and map panel. GEE ui libraries were used to build this layer that connects the backend ‘data acquisition layer’ and ‘operation layer’. The following sections explain the operation behind each tier.

GEE JavaScript libraries were used to retrieve the LST and landcover parameters for the whole Australia. The core libraries revolve around data processing, retrieval, and export functions with several optional arguments to calculate the temperature and landcover parameters. Codes to retrieve LST, NDVI, and NDBI parameters were developed under the ‘operation panel’ in the GEE code editor using JavaScript libraries and functions. Australia’s boundary was taken to map nationwide temperature and landcover data. SA1 shapefile, containing 57, 432 SA1s (cleaned 2016 ABS SA1s) for entire Australia, was used to derive fine-scale nationwide temperature and landcover data.

Land surface temperature (LST) derivation from Landsat 8 SR satellite imagery: Landsat 8 SR satellite is an atmospherically corrected surface reflectance from the Landsat 8 OLI/TIRS sensors containing 5 visible and near-infrared (VNIR) bands and 2 short-wave infrared (SWIR) bands processed to orthorectified surface reflectance, and two thermal infrared (TIR) bands processed to orthorectified brightness temperature. The Landsat 8 SR images were composed into a single image collection by filtering the time period, defining the bounds to Australia and calculating the median of each image. The cloud masking function was applied to remove the clouds from the image collection. LST data derived using MODIS satellite: The afternoon temperature is calculated from MODIS Aqua Land Surface Temperature and Emissivity 8-Day Global 1km. Firstly the images were mosaiced into a single composite. The band ‘LST_Day_1km’ was taken to calculate the afternoon temperature in Kelvin value, which was converted to degree Celsius.

NDVI retrieved from Sentinel-2: An effective index for quantifying green vegetation is NDVI. It normalises green leaf scattering in Near Infra-red wavelengths with chlorophyll absorption in red wavelengths. The value range of the NDVI is -1 to 1. Negative values of NDVI (values approaching -1) correspond to water. Values close to zero (-0.1 to 0.1) generally correspond to barren areas of rock, sand, or snow. Low, positive values represent shrub and grassland (approximately 0.2 to 0.4), while high values indicate temperate and tropical rainforests (values approaching 1). NDVI was derived from the NIR (Sentinel-2 Band 8) and RED (Sentinel-2 Band 4) bands.

NDBI retrieved from Sentinel-2: This index highlights urban areas where there is typically a higher reflectance in the shortwave-infrared (SWIR) region compared to the near-infrared (NIR) region. Also, the Normalized Difference Build-up Index value lies between -1 to +1. The negative value of NDBI represents water bodies, whereas a higher value represents built-up areas. NDBI value for vegetation is low. NDBI was derived from the SWIR (Sentinel-2 Band 11) and NIR (Sentinel-2 Band 8) bands.

The iGEE web tool was published as a SaaS cloud GIS application, which can be found on www.gisonmeta.com. iGEE user interface (Figure 3) represents the third tier on the GEE platform, built from the ‘data acquisition layer’ and ‘operation layer’ using GEE ui libraries. The web tool interface contains a user operation panel and a map panel. The app calls the specific

parameters (land surface temperature or landcover) based on the user’s choice from the user operation panel of the iGEE tool. It then dynamically executes the retrieval algorithm backend and reloads the on-demand results on the map panel. Users need to select a parameter, satellite, time period, data format and a study area to process requests to direct the iGEE tool for computation. Once the computation starts, the tool will display the layers on the right panel. When the computation finishes, the option of ‘Download result’ will appear on the left panel, which is used for exporting the files to the user’s local drive. Refer to Appendix B for the web tool user manual document.

With the derived LST, NDVI and NDBI from the backend ‘operational panel’, the GEE User Interface (UI) libraries were then applied to build the frontend iGEE web tool. Earth Engine App provides access to client-side user interface (ui) widgets through the ui package. The ui package is used to construct graphical interfaces for the scripts executed in the second tier ‘Operation panel’. Table 3 summarises the GEE ui libraries (comprising different widgets) used to build the iGEE web tool.

GEE ui libraries	Description
ui.Panel.Layout()	A widget that can hold other widgets. This is used to create the panel side user interface.
ui.Panel.Layout.flow()	Returns a layout that places its widgets in a flow, either horizontal or vertical.
ui.Label()	Returns a text label to build the status bar of the web tool
ui.Button()	
ui.Select()	This function calls back the results from the operation panel layer
ui.DateSlider()	A draggable target that ranges linearly between two dates. The date slider can be configured to display dates of various interval sizes, including day, 8-day, and year. The value of the slider is displayed as a label alongside it.
ui.Panel.add()	Adds a widget to the panel.

Table 3. Summary of the GEE UI libraries used to build the web tool.

2.2 iHVI Desktop Toolkit

The iHVI toolkit constructs heat sensitivity, heat adaptive capability indicators, and composite heat vulnerability index, which enables modelling of the relationships between heat, environmental and socio-economic factors. This desktop-based application is a first nationwide, dynamic and interactive heat vulnerability assessment toolkit with enhanced workflow, automated analysis and modelling tools, so the indicators and indices can be updated and constructed by the users to serve more applications.

The final integrated Heat Vulnerability Index (HVI) for SA1s is based on the quintile of the composite heat vulnerability score computed from the three indicators: heat exposure index, heat sensitivity index and adaptive capability index. The quintile method takes the observed indicators and provides three cut points so as to divide the SA1s into quintiles. The quintile method takes the observed indicators and provides three cut points so as to divide the SA1s into 1-5 quintiles:

- HVI1: First quintile $(1/3 (A + (B+C+D+E+F+G)/6 - (H+I)/2)$
- HVI2: Second quintile $(1/3 (A + (B+C+D+E+F+G)/6 - (H+I)/2)$
- HVI3: Third quintile $(1/3 (A + (B+C+D+E+F+G)/6 - (H+I)/2)$
- HVI4: Fourth quintile $(1/3 (A + (B+C+D+E+F+G)/6 - (H+I)/2)$
- HVI5: Fifth quintile $(1/3 (A + (B+C+D+E+F+G)/6 - (H+I)/2)$

2.3 iHVI Development Environment

The iHVI desktop toolkit (Figure 4) was developed in the Python 3 environment. The primary packages consist of PySimpleGUIQt, Pandas, Numpy, and other Python built-in packages. PySimpleGUIQt is an integrated package for frontend user interface development. The Pandas and Numpy are mainly used for the heat vulnerability index and heat vulnerability score calculation functions' development. Furthermore, the software compilation is based on the auto-py-to-exe converter, which is a Python-based converter that can compile Python files (.py) to executable files (.exe). The executable file will not require manual installation after downloading.

The iHVI system interface operates based on the iGEE tool and ABS census data. Users can access the iGEE and ABS websites by clicking the buttons on the first row. The data input buttons are on the second row, including LST, NDVI, NDBI, Population Density, Population over 65 years old, Population less than 4 years old, Population Needs Care, Education Level, and Income Level. By default, the “|” below these buttons is “X”, indicating that the input data is empty. When users click on the second row of input buttons, they will be asked to choose files from their local file system, and the “X” will change to a “|.”.

The heat exposure index, heat sensitivity index, and adaptive capability index can be calculated when the correspondingly coloured input data has been filled in. If all the data is uploaded, users can click the blue buttons to calculate the heat vulnerability index and heat vulnerability score.

The output destination is the same directory as the one where the iHVI desktop application is located. Users can define a different output folder by clicking on the “Select folder” button in the bottom right corner. If any errors occur during the calculation, the app will prompt the user with a warning and the user can make changes accordingly.

3. SAMPLE RESULTS OF THE TOOLKIT

This section gives examples of land surface and landcover parameter derivation using the iGEE web tool. First, we present an example of the iGEE web tool to derive land surface temperature data using Landsat 8 SR for a capital city in Australia (Figure 5). Then we demonstrated the capability of iGEE to derive land surface temperature for the entire Australia using the MODIS satellite (Figure 6). We also illustrate the capability of iGEE to derive landcover parameters, for example NDVI for Greater Sydney (Figure 7) and NDBI for Greater Brisbane (Figure 8).

We implemented the open-source desktop app iHVI toolkit to assess the heat vulnerability of the City of Greater Bendigo. The top picture in Figure 9 shows the input data for Greater Bendigo. The LST, NDVI, and NDBI were calculated from the iGEE web tool and the rest of the indicators were obtained from ABS census data. The bottom picture shows the results of the heat vulnerability scores for each SA1s in the City of Greater Bendigo.

4. CONCLUSION

The project will advance the methods and technological infrastructure used to derive assessment metrics from satellite images and open source environmental, social demographic data using machine learning and GIS. In-depth knowledge on urban heat can be generated by modelling the relationships between environmental and social demographic factors. The toolkit will enable researchers and decision makers to access heat exposure, sensitivity, and adaptive capability indicators for intervention strategies. It will empower Australians with information and intelligence for better heat mitigation and adaptation.

ACKNOWLEDGEMENTS

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APPENDIX

The following figures are linked to the individual figures in the main content of this paper.

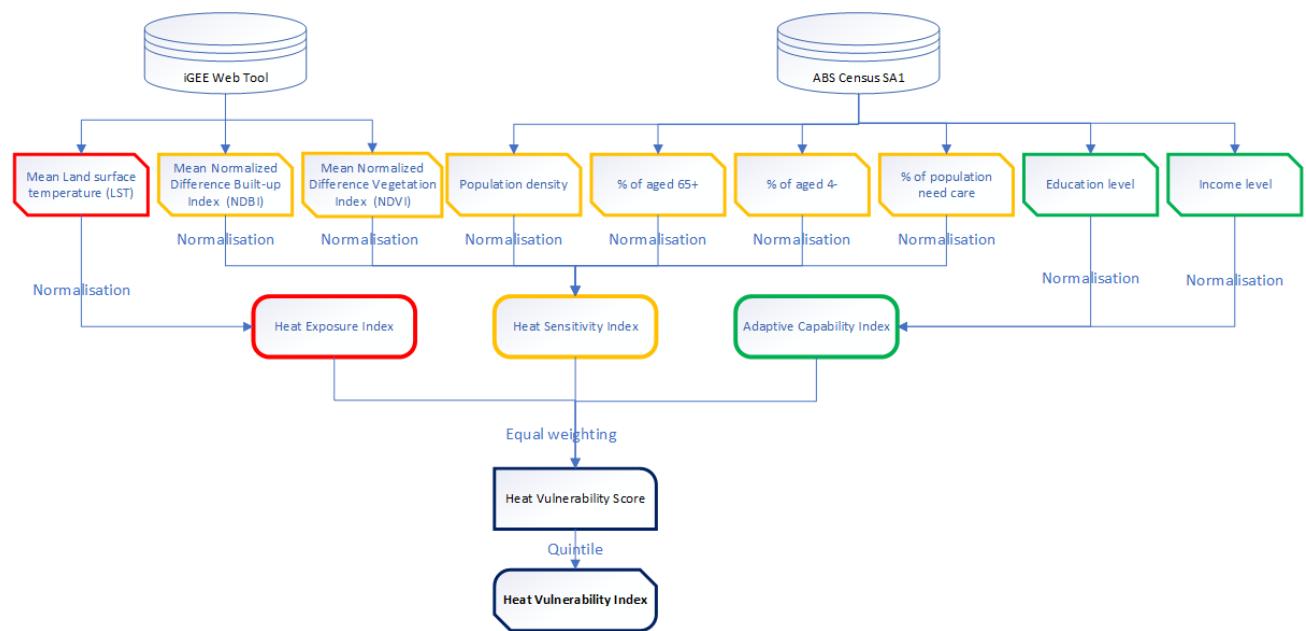


Figure 1: Conceptual methodological framework for Heat Vulnerability Index assessment.

User operation panel

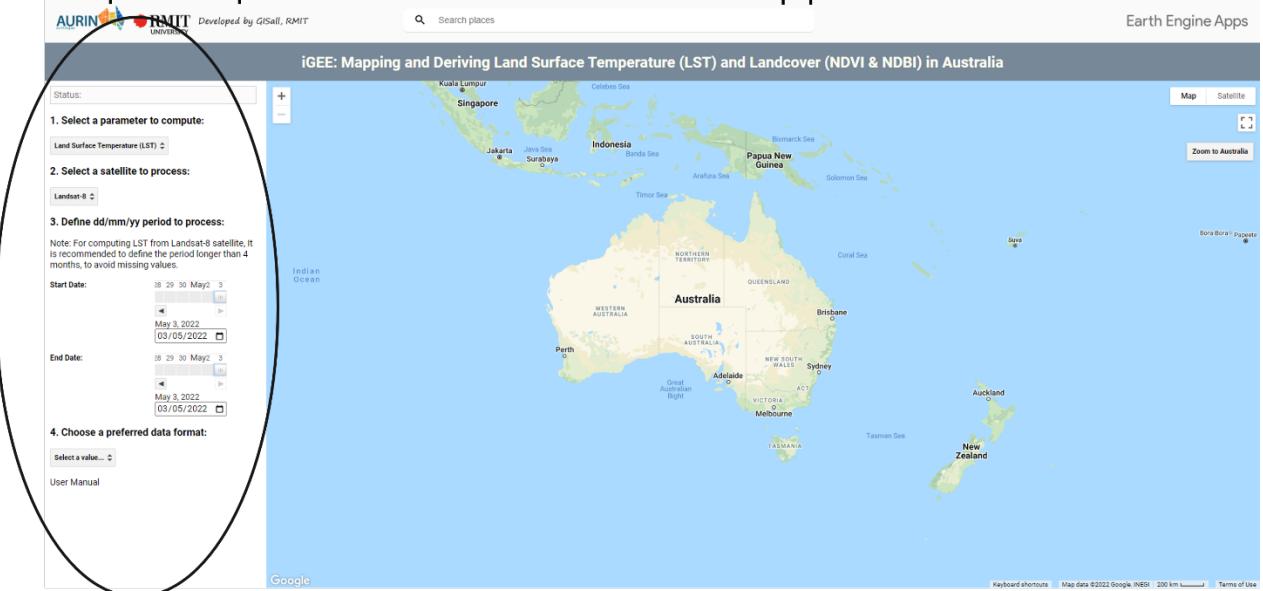


Figure 3. iGEE: Mapping and Deriving Land Surface Temperature (LST) and Landcover (NDVI & NDBI) in Australia.

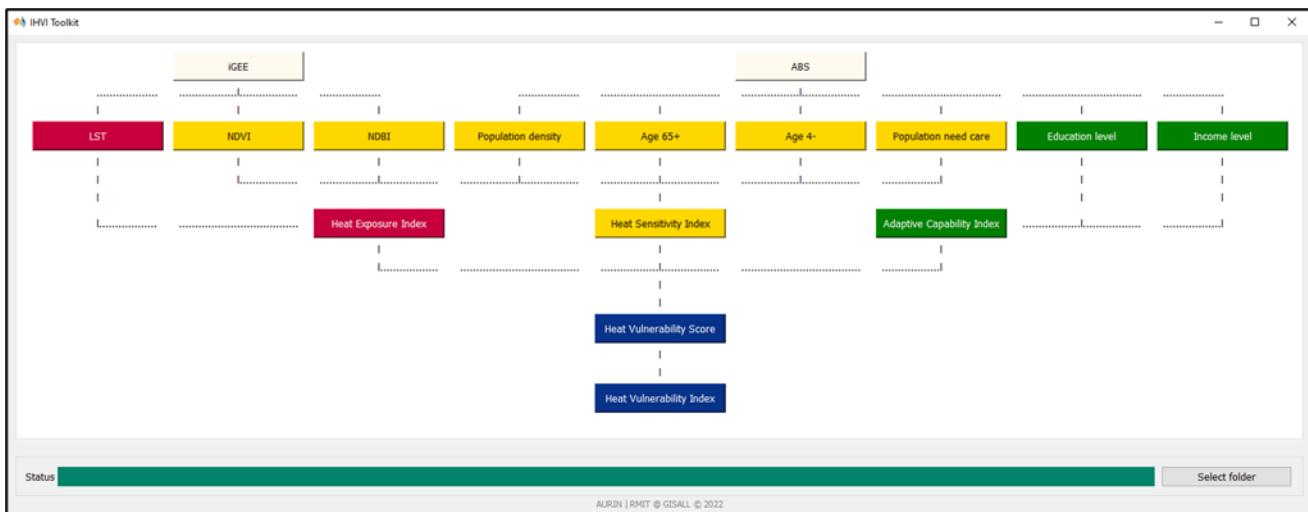


Figure 4. iHVI python desktop toolkit to calculate heat sensitivity, heat adaptive capability indicators, and composite heat vulnerability index

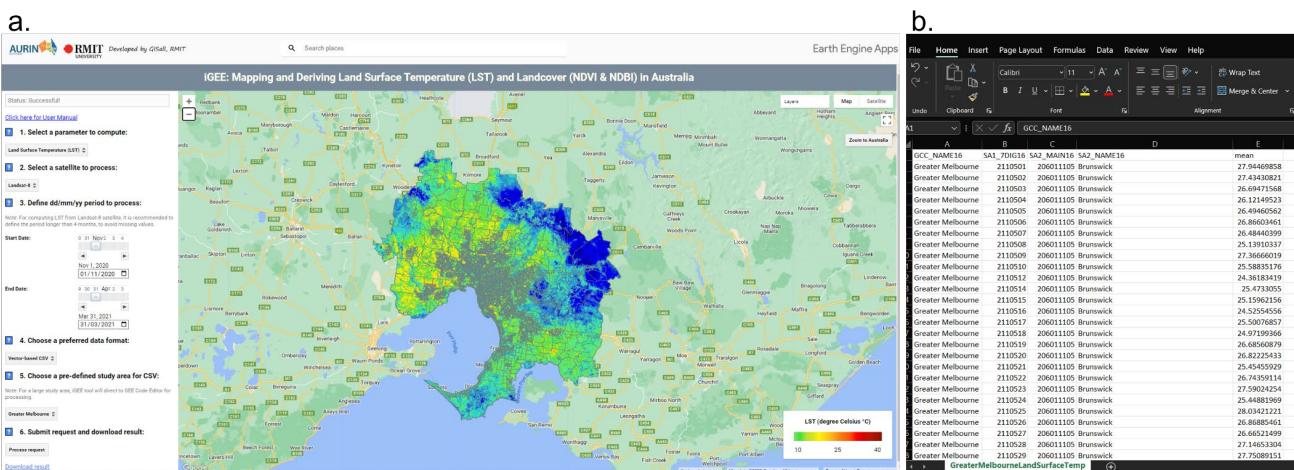


Figure 5. Example showing mean LST for Greater Melbourne using Landsat 8 SR; 5a. shows the iGEE interface used to download the LST; 5b. Downloaded CSV from iGEE web tool showing the mean temperature for Greater Melbourne.

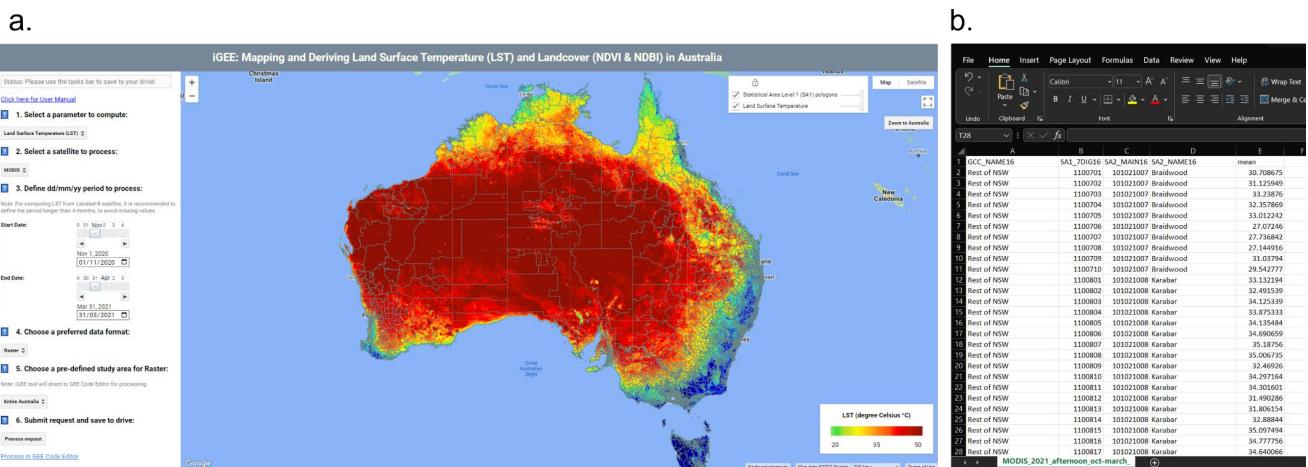


Figure 6. Example showing mean LST for entire Australia using MODIS; 6a. shows the iGEE interface used to download the LST; 6b. Downloaded CSV from iGEE web tool showing the mean temperature for Australia.

a.

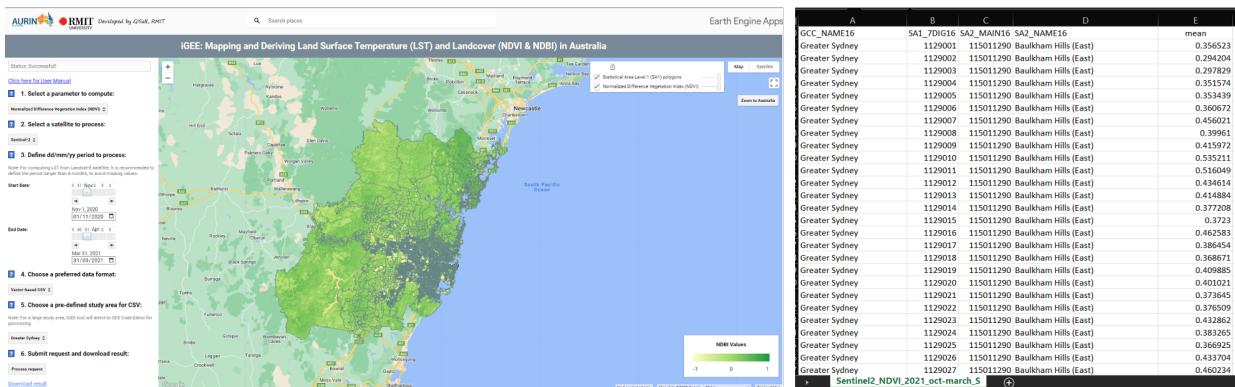


Figure 7. Example showing mean NDVI for Greater Sydney using Sentinel-2; 6a. shows the iGEE interface used to download the LST; 7b. Downloaded CSV from iGEE web tool showing the mean NDVI values for Greater Sydney.

b.

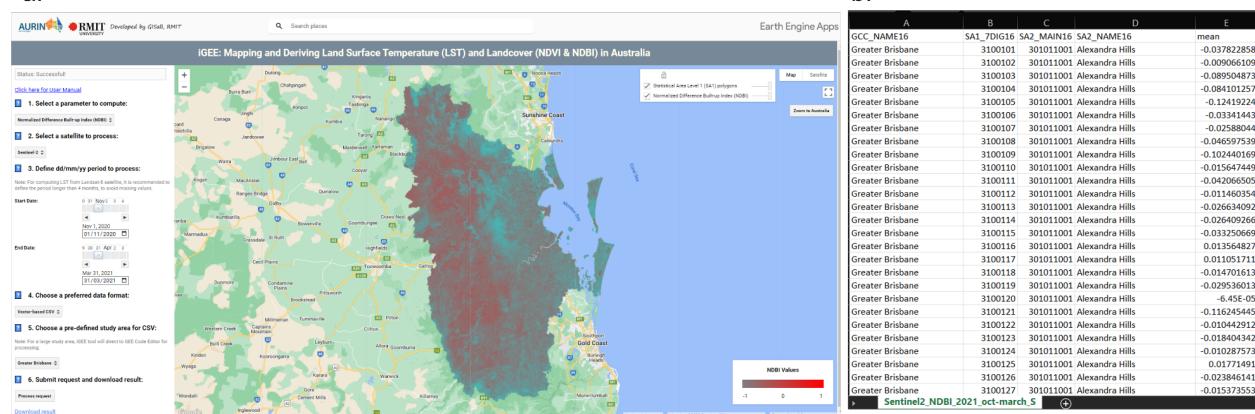


Figure 8. Example showing mean NDBI for Greater Brisbane using Sentinel-2; 8a. shows the iGEE interface used to download the LST; 8b. Downloaded CSV from iGEE web tool showing mean NDBI values for Greater Brisbane.

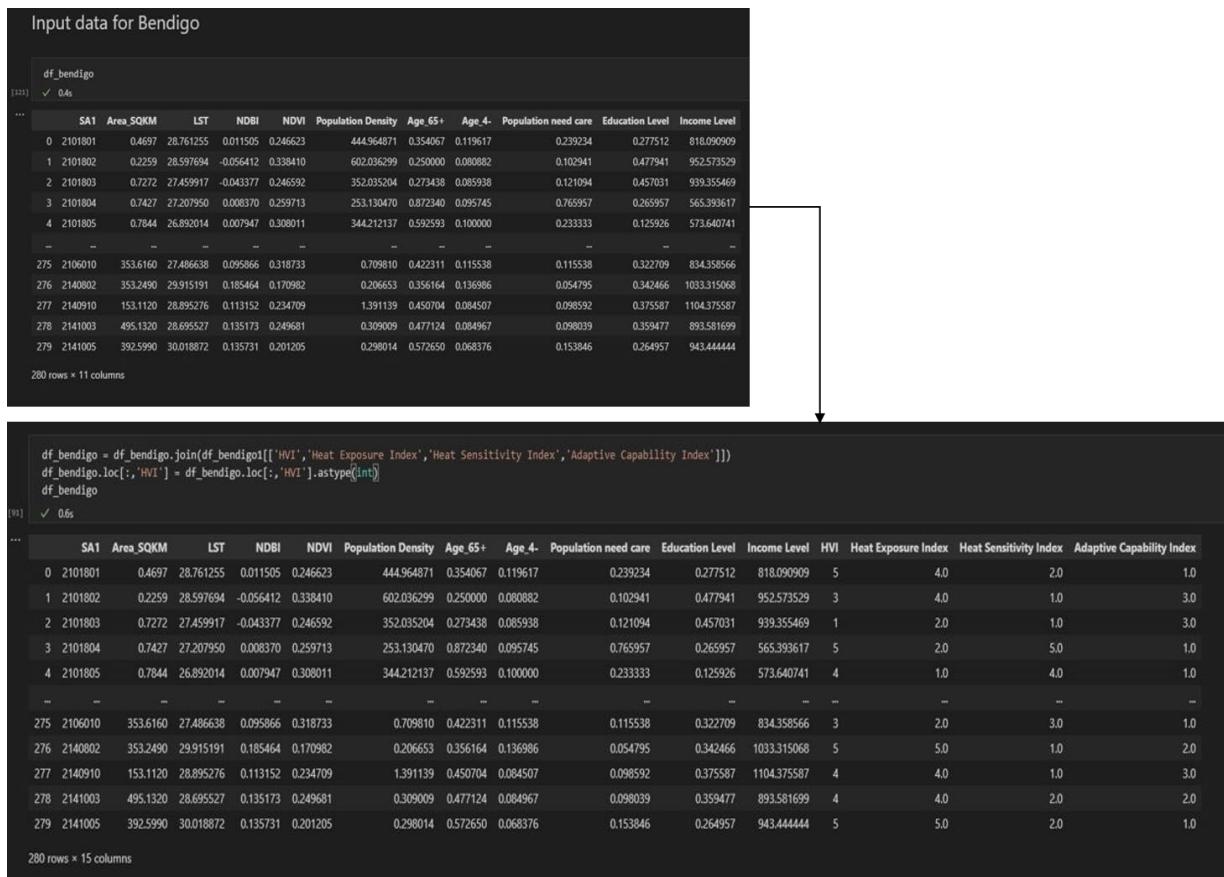


Figure 9. Example showing the iHVI toolkit used to calculate the heat vulnerability score for the City of Greater Bendigo