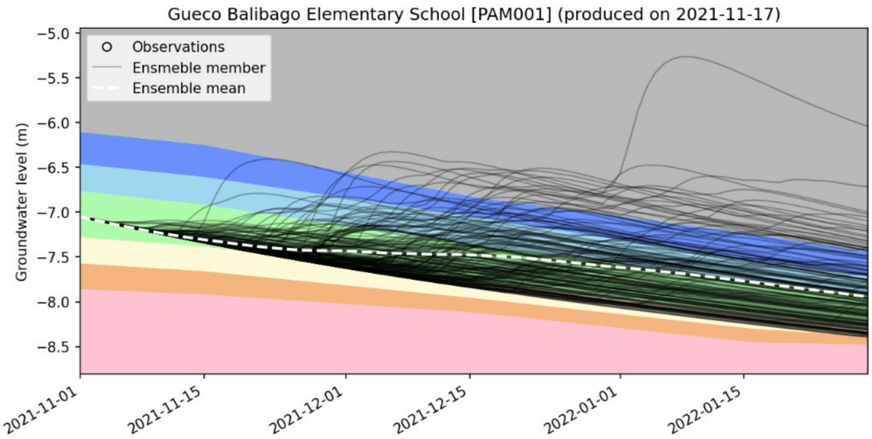
PhiGO Seasonal Groundwater Forecasting System

Monitoring and Forecasting Programme

Open Report OR/21/066



BRITISH GEOLOGICAL SURVEY

MONITORING AND FORECASTING PROGRAMME

OPEN REPORT OR/21/066

PhiGO Seasonal Groundwater Forecasting System

Jonathan D Mackay, Andrew Barkwith, Maria Aileen Leah G Guzman

Keywords

Report; PhiGO, groundwater, forecasting.

Bibliographical reference

MACKAY, J.D., BARKWITH, A., Guzman, M.A.L.2022. PhiGO Seasonal Groundwater Forecasting System. *British Geological Survey Open Report*, OR/21/066. 21pp.

Keyworth, Nottingham British Geological Survey 2022

BRITISH GEOLOGICAL SURVEY

The full range of our publications is available from BGS shops at Nottingham, Edinburgh, London and Cardiff (Welsh publications only) see contact details below or shop online at www.geologyshop.com

The London Information Office also maintains a reference collection of BGS publications, including maps, for consultation.

We publish an annual catalogue of our maps and other publications; this catalogue is available online or from any of the BGS shops.

The British Geological Survey carries out the geological survey of Great Britain and Northern Ireland (the latter as an agency service for the government of Northern Ireland), and of the surrounding continental shelf, as well as basic research projects. It also undertakes programmes of technical aid in geology in developing countries.

The British Geological Survey is a component body of UK Research and Innovation.

British Geological Survey offices

Nicker Hill, Keyworth,
Nottingham NG12 5GG
Tel 0115 936 3100

BGS Central Enquiries Desk
Tel 0115 936 3143
email enquiries@bgs.ac.uk

BGS Sales
Tel 0115 936 3241
email sales@bgs.ac.uk

The Lyell Centre, Research Avenue South,
Edinburgh EH14 4AP
Tel 0131 667 1000
email scotsales@bgs.ac.uk

Natural History Museum, Cromwell Road,
London SW7 5BD
Tel 020 7589 4090
Tel 020 7942 5344/45
email bgslondon@bgs.ac.uk

Cardiff University, Main Building, Park Place,
Cardiff CF10 3AT
Tel 029 2167 4280

Maclean Building, Crowmarsh Gifford,
Wallingford OX10 8BB
Tel 01491 838800

Geological Survey of Northern Ireland, Department of Enterprise, Trade & Investment, Dundonald House, Upper Newtownards Road, Ballymiscaw,
Belfast, BT4 3SB
Tel 01232 666595
www.bgs.ac.uk/gsni/

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon SN2 1EU
Tel 01793 411500 Fax 01793 411501
www.nerc.ac.uk

UK Research and Innovation, Polaris House,
Swindon SN2 1FL
Tel 01793 444000
www.ukri.org

Website www.bgs.ac.uk
Shop online at www.geologyshop.com

Contents

FIGURES

TABLES

1 Introduction

This report provides an overview of the seasonal (90-day) groundwater level forecasting system for the Philippines that was developed as part of the NERC-Newton fund Philippines Groundwater Outlook (PhiGO) project (NE/S003118/1). The system builds on other operational groundwater level forecasting systems developed at the BGS, such as the UK Hydrological Outlook (Prudhomme et al., 2017). Forecasts are made at the borehole scale across a network of observation boreholes using the BGS AquiMod groundwater model (Mackay et al., 2014a) driven by numerical weather prediction forecasts. However, this system has been customised with the Philippine case study in mind. More specifically, it has been developed to work alongside a telemetered network of boreholes operated by Ateneo de Manila University (ADMU) and owned by the National Water Resources Board (NWRB) under the Groundwater Management Plan (GMP) project. Groundwater level data have only been collected since 2019 and the network is continually expanding. Accordingly, a number of additional features have been included, such as automated recalibration of the AquiMod models as more observation data become available; and the ability to automatically generate new AquiMod groundwater models as the telemetered network expands. Climate observation data are also relatively sparse and, therefore, the system makes use of freely-available global gridded datasets.

This report outlines the scientific background and methodology of the forecasting system. It also summarises the principal outputs, which are published online via a free-to-view web-delivery platform (https://mapapps.bgs.ac.uk/phigo/). The report begins with an overview of the process-based BGS AquiMod groundwater model which underpins the groundwater level forecasts as well as the model calibration and evaluation approach used in the forecasting system. Section 3 provides more details of the input data used to drive the forecasts before Section 4 gives an overview of the underlying processes in the forecasting system. Finally, a description of the main system outputs is given in Section 5.

2 AquiMod groundwater model

2.1 OVERVIEW

AquiMod is a simple, lumped conceptual groundwater model that simulates daily groundwater level time series at a borehole. It is driven by daily time series of rainfall and potential evaporation (PET) and links simplified equations of soil drainage, unsaturated zone flow and saturated groundwater flow (Figure 1). Each of these three components use model parameters that define site-specific hydrogeological characteristics of the groundwater catchment surrounding the borehole. These include soil type, land cover and aquifer storage and permeability. A number of these parameters are typically unknown and, therefore, must be calibrated.

AquiMod can also incorporate different model structures (process equations) to represent the saturated zone. For example, a one-, two- or three-layer representation of the saturated zone can be used, which represents different levels of vertical heterogeneity for aquifer permeability and storage. Past work has shown that the suitability of each structure is site-specific (Mackay et al., 2014b) and, therefore, must also be calibrated. A detailed explanation of AquiMod, its model equations, parameters and available model structures are given in Mackay et al. (2014a). The reader is referred to this document for further details.

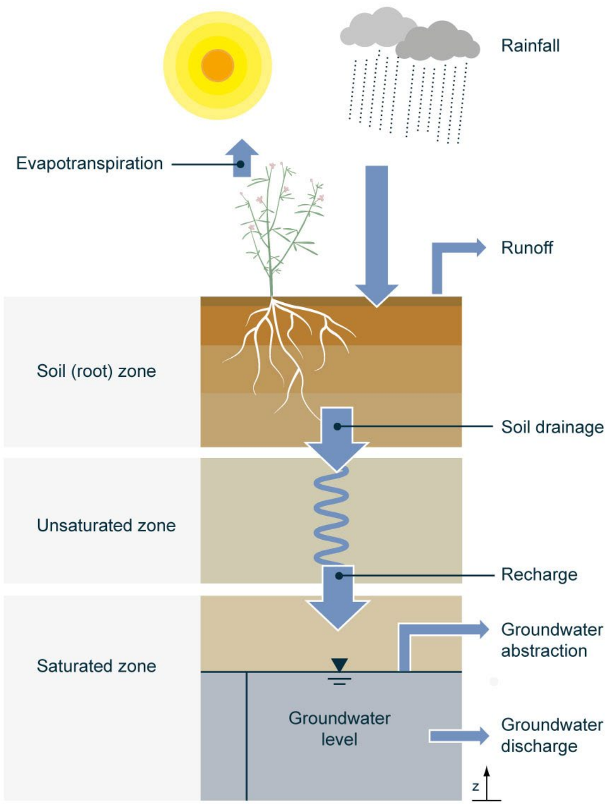


Figure 1: Generalised structure of AquiMod. Source: BGS © UKRI

2.2 MODEL CALIBRATION

The AquiMod calibration procedure is undertaken for each borehole separately to account for site-specific hydrogeological characteristics. Calibration is based on goodness-of-fit to historical observed groundwater level time series (section 3.1) when driven with the best available observation climate data (section 3.2). For a given borehole, the AquiMod parameters and structure are calibrated to achieve the most efficient simulation of available historical groundwater level data using the Nash-Sutcliffe Efficiency (NSE). This performance measure provides a reliable assessment of overall process realism and goodness of fit to groundwater level time series. Model parameters that can be related to catchment information are fixed to improve the efficiency of the calibration problem. For the Philippines these data are not routinely available at the national scale. It was, however, possible to fix the soil field capacity and wilting point parameters which are taken from the World Harmonised soil database (Fischer et al., 2008). In addition, the representative aquifer length and bottom elevation parameters are fixed to arbitrary values of 1 km and 50 m below the minimum observed groundwater level at the borehole respectively. This is done due to the known interaction between these parameters and other calibration parameters in the model (Mackay et al., 2014b). While this approach helps to improve the efficiency of the calibrated model, it does mean that some of the calibrated parameters (in particular the aquifer hydraulic conductivity) are not likely to be representative of the real field properties.

The remaining parameters which include those that control the percolation of soil drainage through the unsaturated zone and hydraulic properties of the aquifer are then calibrated using six different saturated zone model structures including: a one-layer model (fixed permeability and specific yield); two- and three-layer models with vertically-variable permeability and fixed specific yield; two- and three-layer models with variable permeability and variable specific yield; and a “cocktail glass” representation of conductivity change with depth (Williams et al., 2006). Depending on the complexity of the saturated zone model structure, the number of calibration parameters ranges from 8 to 13. The optimal structure-parameter combination is obtained for each borehole using the Shuffled Complex Evolution global optimisation algorithm (Duan et al., 1993) which has shown to be a reliable optimisation algorithm for hydrological modelling.

2.3 MODEL EVALUATION

There are two sources of information for model evaluation. Firstly, the NSE used to evaluate the calibrated models based on a comparison of the simulated and observed daily groundwater level data available for each borehole. The NSE is a positively-oriented metric equal to one minus the ratio of error variance to the variance of the observation data with a range of $-\infty$ to 1, where 1 is a perfect fit to the observation data (zero error variance). A score of 0 (error variance equal to the variance of the observation data) is equivalent to using the mean of the observation data as the predictor. Anything less than 0 is worse than this. A high NSE indicates that the model captures the overall groundwater level dynamics (timing, amplitude, variability) efficiently. A qualitative descriptor of the model performance is given which can fall into one of five categories (Table 1).

Description	NSE
Excellent	NSE ≥ 0.9
Very good	0.8 ≤ NSE < 0.9
Good	0.7 ≤ NSE < 0.8
Satisfactory	0.5 ≤ NSE < 0.7
Poor	NSE < 0.5

Table 1: Qualitative descriptors of model performance

Additionally, a visual inspection of the simulated groundwater level time series against the observations is available for each borehole (Figure 2). For this, two different models are calibrated using different amounts of available observed groundwater level data to test the robustness of the calibration procedure. The “operational model” is the model used operationally to deliver the forecasts and is calibrated using all of the available observed groundwater level data. The “evaluation model” is an additional calibrated model which is calibrated using only half of the available observed groundwater level data. The difference in performance between the operational and evaluation model gives some indication of the robustness of the calibration procedure. More specifically, significant divergence between the model hydrographs indicates that the model behaviour is poorly constrained due to a lack of observation data. As more observation data become available, it is expected that model behaviour will converge to a more robust representation of the groundwater systems.

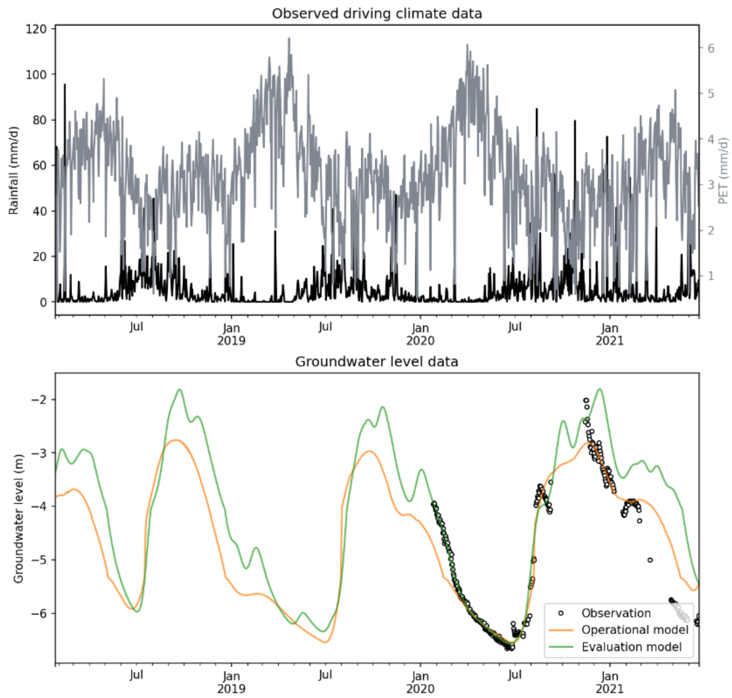


Figure 2: Example model evaluation plot for ILOILO2 borehole. The top graph shows the driving climate data. The bottom graph shows how well the operational and evaluation models capture the observations.

3 Input data

3.1 GROUNDWATER LEVEL OBSERVATIONS

As part of the PhiGO and the GMP projects, ADMU have established a network of telemetered boreholes in critical urban areas identified by NWRB. As of this writing a total of 18 telemetered boreholes exist with plans of expanding this number in the future. For the PhiGO project, the boreholes situated in Pampanga and Iloilo (10 as of writing) are used (Figure 3). These data are hosted by ADMU. Data are accessible via an application programming interface (API), which allows data to be obtained instantly.

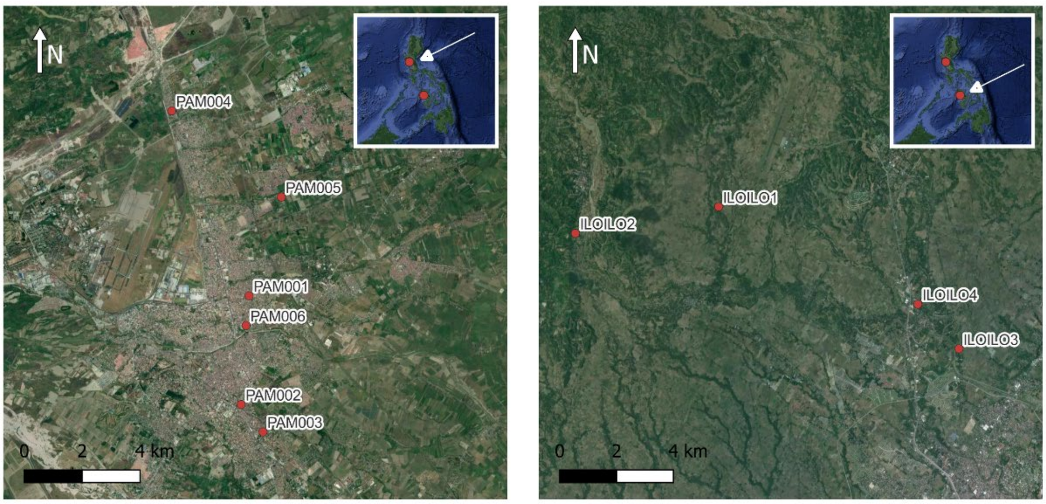


Figure 3: Telemetered boreholes in Pampanga (left) and Iloilo (right) as of time of writing. Imagery ©2022 Maxar Technologies, Google, Imagery ©2022 TerraMetrics, Map Data ©2022.

3.2 CLIMATE OBSERVATION DATA

Observational meteorological data are needed to calibrate, validate and initialise the model. Frequently updated observations of rainfall and PET are not readily available at the national scale in the Philippines. A number of global gridded datasets of rainfall exist (Table 2); however, only the ERA5 reanalysis dataset provides updated rainfall and PET data at the frequency required for this seasonal groundwater level forecasting system. Accordingly, these data are used. These data are hosted on the Climate Data Store (CDS) API.

Dataset	Resolution	Timespan	Reference/source
APHRODITE (v1001)	0.25°	1951-2015	Yatagai et al. (2012) APHRODITE's Water Resources (2020)
APHRODITE (v1901)	0.25°	1998-2015	
TRMM (3B42)	0.25°	1998-2019	TRMM (2011)
GPM (v06)	0.1°	2000-present	Huffman et al. (2019)
Princeton	0.25°	1948-2016	Sheffield et al. (2006)
ERA5	0.25°	1979-present	Hersbach et al. (2018)

Table 2: Global gridded rainfall datasets used as part of the rainfall data comparison for PhiGO.

As part of the PhiGO project, a rigorous comparison of available global rainfall datasets was undertaken to establish the relevant strengths and weaknesses of each. This was done by comparing the gridded rainfall data to observation records collected at 12 Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) meteorological stations (see Figure 8, APPENDIX 1 for station locations). Figure 4 shows the statistics calculated for each gridded rainfall product to investigate different aspects of the rainfall data including seasonal bias, bias in rainfall extremes, bias in rain day frequency and co-variability.

The mean absolute seasonal bias (Figure 4a) was calculated by estimating the mean absolute bias of accumulated rainfall over four three-month periods (MAM, JJA, SON, DJF). For Iloilo, the ERA5 data shows the second-largest mean absolute seasonal biases (1.8 mm d^{-1}). For Pampanga, the ERA5 data shows errors in line with the most accurate APHRODITE observation records with a mean absolute seasonal bias of 1.3 mm d^{-1}.

For rainfall extremes, the bias in the 99th percentile daily rainfall was calculated (Figure 4b). The ERA5 data show some of the largest negative biases of -26.8 and -33.2 mm d^{-1} respectively indicating that the ERA5 data does not capture daily rainfall extremes adequately. The ERA5 data also show the largest bias in number of rain days for Iloilo and Pampanga where number of rain days is overestimated by 97% and 83% respectively (Figure 4c). This corroborates the rainfall extreme comparison indicating that rainfall is spread across too many days of the year leading to underestimation of extremes.

Finally, co-variability between the daily gridded and meteorological station rainfall data was calculated using the coefficient of variation (R^2) (Figure 4d). Here, the ERA5 data is not the worst-performing rainfall product, but the correlation scores are still low indicating only a very weak coherence between observations and the gridded data. The R^2 was calculated to be 0.19 and 0.31 for Iloilo and Pampanga respectively.

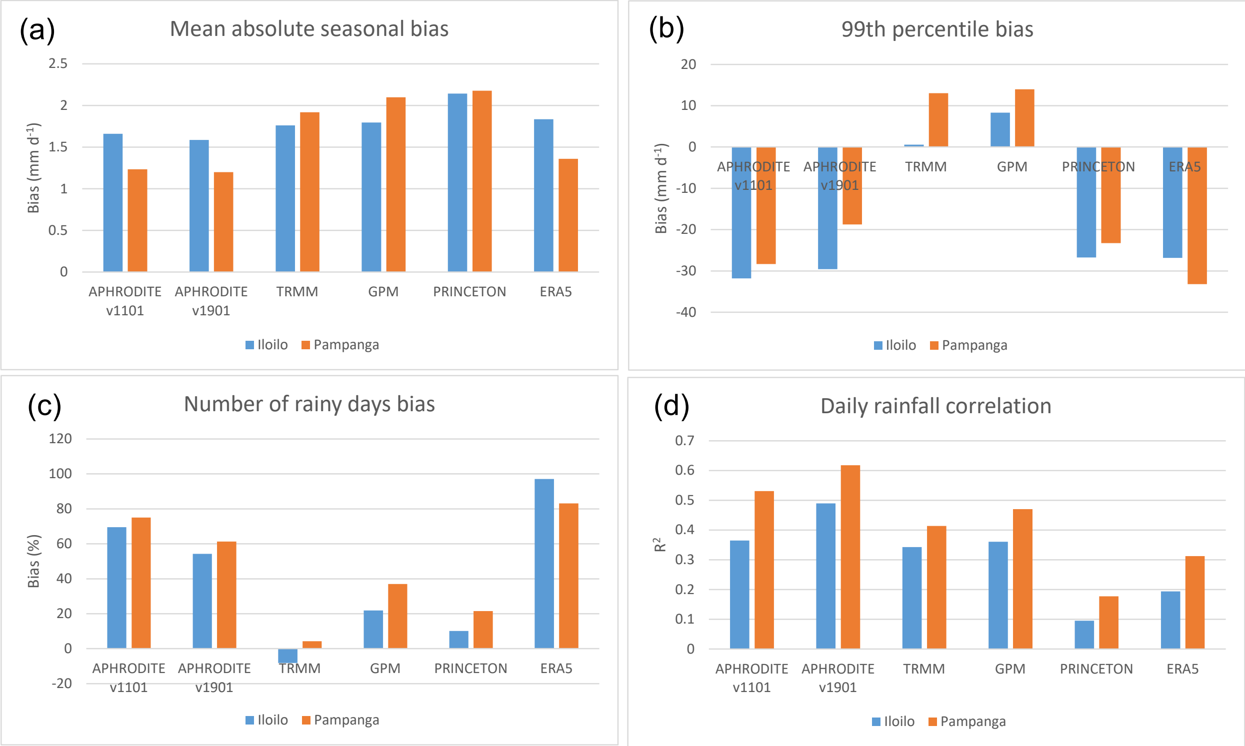


Figure 4: Summary statistics of gridded rainfall data mean biases when compared to the PAGASA meteorological station data collected in Iloilo and Pampanga.

The rainfall data analysis shown here indicates that there are weaknesses in the ERA5 rainfall data. However, there is no suitable alternative product that provides regular (at least monthly) updated rainfall and PET to drive this forecasting system. The translation of bias from ERA5 into the final groundwater level forecasts are unknown and are likely to be dependent on local hydrogeological characteristics which control the responsiveness of groundwater levels to the driving climate. The advantage gained from including more accurate observation data is also likely to be site-specific. Even so, it is recommended that, if more accurate observation data become available in the future, these should be incorporated into the forecasting system.

3.3 SEASONAL CLIMATE FORECASTS

Seasonal climate forecasts of rainfall and PET are used to drive the groundwater level forecasts. The CDS hosts a number of freely available seasonal climate forecast products, which are released 13th day of each month at 12:00UTC. Daily seasonal forecasts of rainfall and PET covering the 90-day period from the beginning of the month are used from five forecasting centres including the Euro-Mediterranean Center on Climate Change (CMCC), Deutscher Wetterdienst (DWD), European Center for Medium-Range Weather Forecasting (ECMWF), Meteo France and the UK Met Office. Each forecasting centre releases an ensemble global-scale of seasonal forecasts. These are combined to generate a grand-ensemble of climate forecasts made up of ~200 ensemble members. All ensemble members are assumed independent and of the same random process and, therefore, equally likely.

4 Forecasting procedure

The forecasting system is scheduled to run at 14:00 UTC every day of the year. During a run, the system undertakes a number of processes which are summarised in Figure 5 and described in more detail below.

Determine borehole network (daily)

The first process determines the number of and location of telemetered boreholes by querying the borehole telemetry database via the ADMU API.

Update groundwater level archive (daily)

The latest observed groundwater level data are extracted and stored. The most recent groundwater level observation for each borehole is reported to the web delivery platform to update the current groundwater level status. If a recent groundwater level observation does not exist for any borehole, the mean simulated groundwater level for the current day is reported instead.

Get latest ERA5 reanalysis data (13th day of month only)

Each month the latest ERA5 observation climate data are extracted for each borehole. These data are used to drive the AquiMod model up to the first day of the seasonal forecast.

Calibrate AquiMod (13th day of month only)

AquiMod is calibrated against the full observed groundwater level archive up to the first day of the seasonal forecast.

Quantitative and graphical model evaluation (13th day of month only)

The model evaluation steps outlined in section 2.3 are undertaken and made available to the web delivery platform.

Generate contextual groundwater level bands (13th day of month only)

The calibrated AquiMod models are run over the full ERA5 observation period (1980 to present) and the simulations are used to determine qualitative groundwater level bands that can be used to put the forecast groundwater levels in the context of historical groundwater levels. Bands are calculated for each month of the year by extracting the percentile points of historical groundwater levels according to Table 3.

Groundwater level category	Percentile range in distribution	HEX colour code
Exceptionally high	>95	#A8A8A8
Notably high	87-95	#4675FD
Above normal	72-87	#87CEEA
Normal	28-72	#9AFA98
Below normal	13-28	#FEF8CF
Notably low	5-13	#F4A361
Exceptionally low	<5	#FFB5C6

Table 3: Qualitative groundwater level bands. The colours are used for display purposes on the web delivery platform.

Get latest seasonal weather forecasts (13th day of month only)

The latest daily seasonal forecasts of rainfall and PET covering the 90-day period from the beginning of the month are extracted via the CDS API.

Initialise AquiMod (daily)

The AquiMod groundwater model has internal “memory” due to water storage in the soil, unsaturated zone and saturated zone modules which are controlled by antecedent conditions. If these are not initialised properly, this can introduce deficiencies into the groundwater level forecasts. To ensure the models are optimally initialised, the most recent three years of ERA5 rainfall and PET data are used to “spin up” all of the models. The latest groundwater level measurement is also imposed on the saturated zone to achieve optimal initial groundwater level conditions in the model. If groundwater level data are not available on the current forecast day, the latest simulated level based on the observed driving climate data is used.

Run AquiMod (daily)

All AquiMod models are run for the 90-day forecast period starting from the first day of the current month. As more recent groundwater level observation data becomes available for the current month, the model is initialised based on these and the forecasts provided to the Web-delivery platform are adjusted accordingly.

Generate forecast plots (daily)

Once all forecasts have been produced, the system generates a series of forecast plots. These are explored in more detail in the next section.

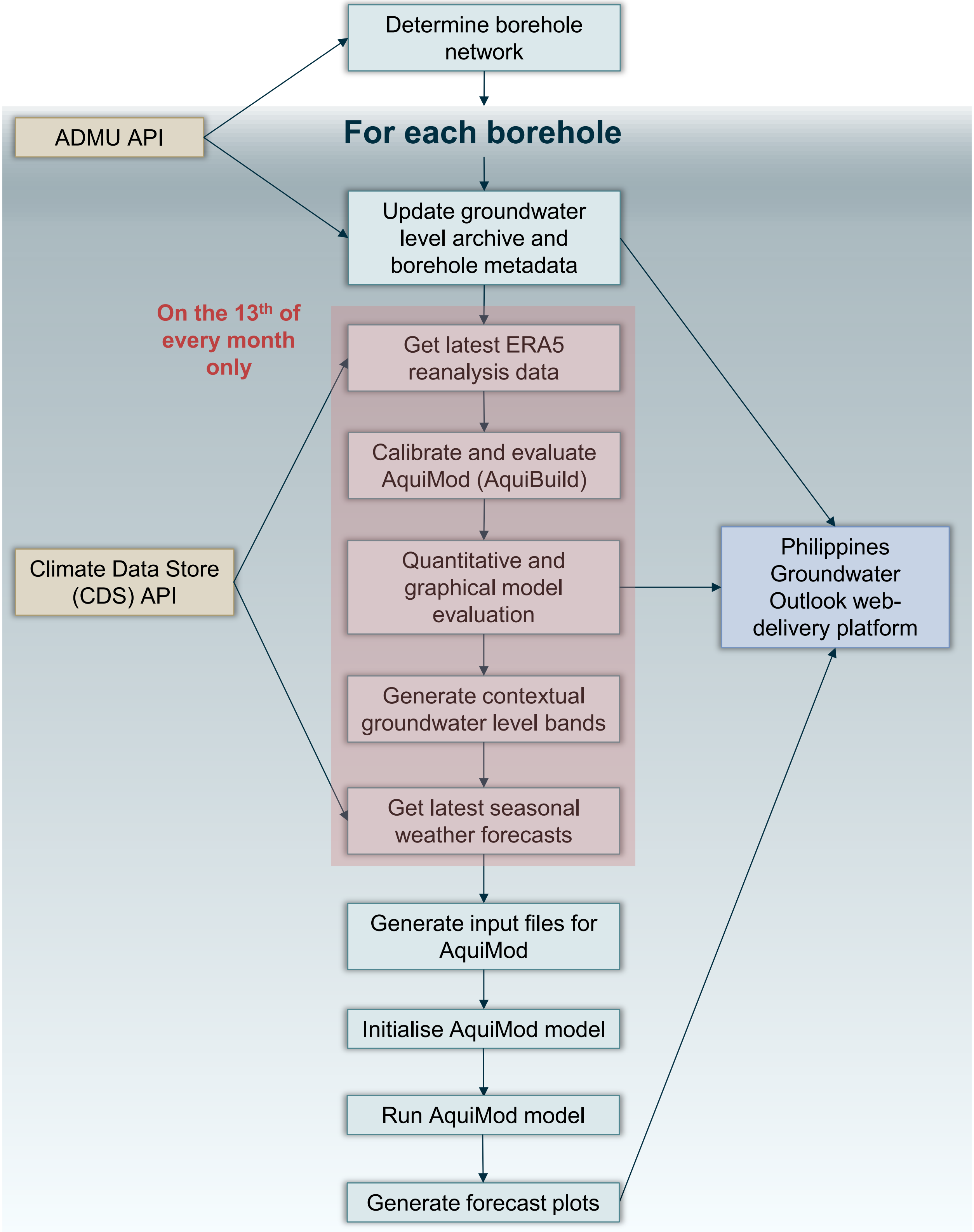


Figure 5: Overview of ordering of groundwater level forecasting workflow processes (central boxes) with input data sources (left) and data delivery to the web delivery platform (blue box). The processes highlighted by the red box are only performed on the 13th of every month.

5 Forecasting system outputs and interpretation

5.1 CURRENT GROUNDWATER LEVEL SITUATION

The most up-to-date map of the current groundwater level situation is provided by the forecasting system and displayed on the web delivery platform (Figure 6). The current groundwater level at each borehole is based on the latest observed groundwater level data. If there are no recent observations, the mean simulated groundwater level for that day is used instead. On the web delivery application, boreholes are coloured according to where they lie within pre-defined bands on the distribution of historical observed groundwater levels for each month (Table 3). This information provides a useful comparison of the current groundwater situation in the context of historical norms. The spatial applicability of a borehole's situation (band) will depend strongly on local hydrogeological controls, but in most cases, it should only be considered to be representative of groundwater resources up to a maximum of several kilometres away (in some cases it will be much less than this).

Where local hydrogeological information and/or information on land and water use is available, it may be possible to relate the current groundwater level situation at a borehole to local susceptibility and impacts. For example, when the current groundwater level situation is below the normal range (lower than the 28th percentile of levels for that time of year), groundwater resources in the vicinity of that borehole are more susceptible to experiencing anomalously low groundwater levels in the future if drier-than-average conditions persist. In extreme cases, this may be classified as a groundwater drought. Depending on the hydrogeological setting, lower than average groundwater levels can be associated with reduced baseflow to nearby, groundwater-fed rivers. Nearby groundwater abstraction yields may also be inhibited, particularly in poorly-developed, shallow abstraction wells.

Similarly, if the current groundwater level situation is above the normal range (higher than the 72nd percentile of levels for that time of year), groundwater resources in the vicinity of that borehole are more susceptible to experiencing anomalously high groundwater levels if wetter-than-normal conditions persist. Depending on the hydrogeological setting and time of year, higher than average groundwater levels may be associated with increased baseflow to nearby groundwater-fed rivers or activation of ephemeral streams that typically don't flow at that time of year. In some cases, higher than average groundwater levels may be associated with increased susceptibility of local areas to groundwater flooding.

Because groundwater typically responds more slowly to rainfall inputs than surface water river systems, the current groundwater level condition is a useful first-order indicator of near-future susceptibility to groundwater extremes in the vicinity of each borehole. However, a more detailed assessment of future susceptibility to groundwater extremes based on weather forecasts can be obtained from the seasonal forecast plots.

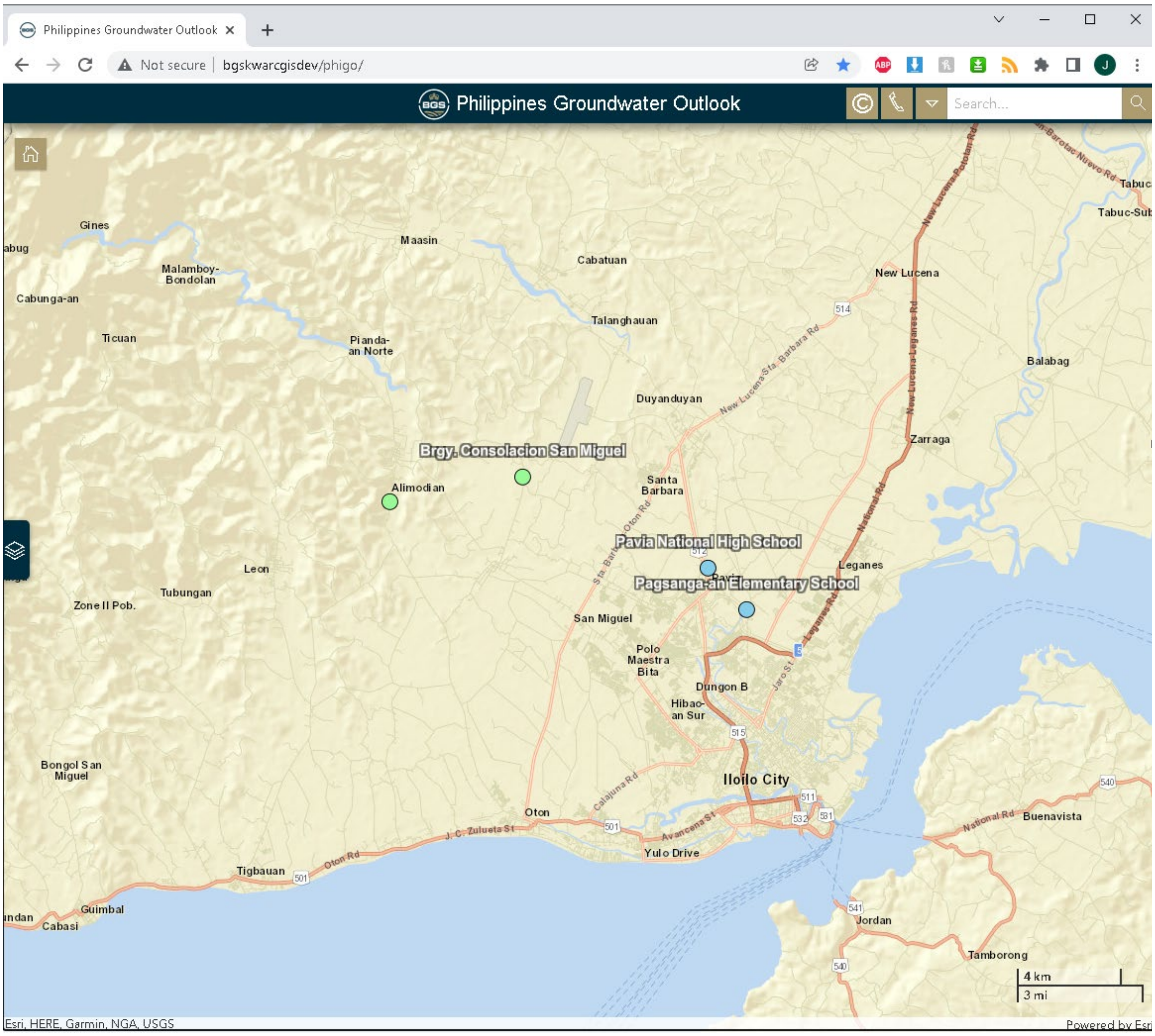


Figure 6: Philippines Groundwater Outlook zoomed into Iloilo region with boreholes shown by coloured circles where colours indicate the current groundwater level relative to historical groundwater levels at this time of year. Imagery ESRI, HERE, Garmin, NGA, USGS.

5.2 LATEST FORECAST PLOTS

The latest forecast plots are published every day on the web delivery platform. An example plot for the PAM001 borehole is shown in Figure 7. They provide a more detailed assessment of future susceptibility to groundwater extremes over the following 90-days based on the seasonal forecasts of future weather patterns. For each borehole a “spaghetti” time-series is provided to present the trajectory of individual ensemble members within the probabilistic seasonal forecasts. The latest groundwater level observations (if they exist) are also shown, overlain on colour-coded groundwater level bandings. The exact way in which these forecasts are used operationally will depend on the user’s goals, but there are some general principles that are likely to be useful for most applications.

Firstly, the spread of the ensemble provides an indication of how much confidence there is in a particular forecast. Where the spread is small and constrained within a single groundwater level band, there is good agreement between the ensemble members and high confidence that the groundwater level will reside in that band. Typically, the confidence in the forecast reduces when looking further ahead in time. Of course, the forecasts may be biased due to errors in the historical/future climate data and/or AquiMod models. The latter of these can be assessed through considering the model evaluation detailed previously. Therefore, high confidence does not necessarily translate to high likelihood of occurrence in reality.

Related to this is the forecast skill. Previous analysis of seasonal groundwater level forecasting skill (Mackay et al., 2015) has shown that the skill of forecasts including their reliability, resolution and discrimination deteriorate with lead time. The ability to make beneficial decisions based on the forecasts is, therefore, likely to deteriorate when looking further into the future.

The ensemble mean should, on average, provide the most skilful forecast of future groundwater levels. It is therefore recommended that in most operational settings, this forecast is used in some capacity to inform decision-making. The individual ensemble members may also provide useful information, particularly if the user wishes to establish plausible worst-case scenarios. In this case, users may wish to use the tails of the ensemble distribution to explore these plausible scenarios.

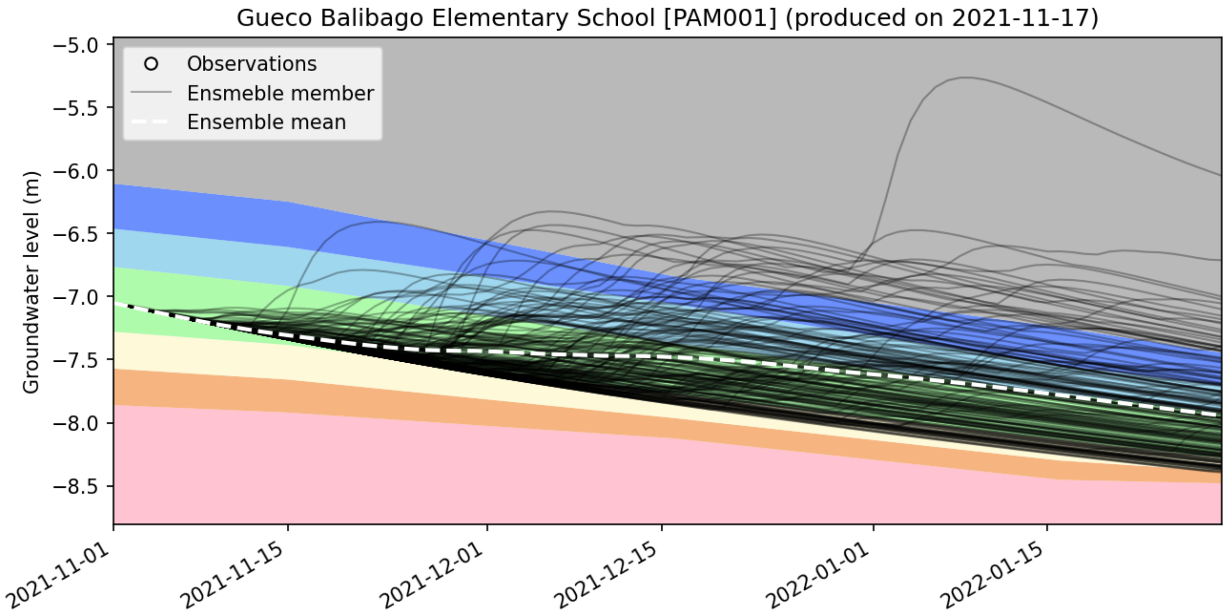


Figure 7: Example seasonal forecast plot for PAM001 borehole (initialised 1st November 2021).

References

British Geological Survey holds most of the references listed below, and copies may be obtained via the library service subject to copyright legislation (contact libuser@bgs.ac.uk for details). The library catalogue is available at: https://of-ukrinerc.olib.oclc.org/folio/.

Asian Precipitation - Highly-Resolved Observational Data Integration Towards Evaluation of Extreme Event (APHRODITE) Water Resources web page: http://aphrodite.st.hirosaki-u.ac.jp/products.html, Accessed January 2020.

Duan, Q.Y.; Gupta, V.K.; Sorooshian, S. 1993. Shuffled complex evolution approach for effective and efficient global minimization. Journal of Optimization Theory and Applications, 76, 501-521. https://doi.org/10.1007/BF00939380.

Fischer, G.; Nachtergaele, F.; Prieler, S.; van Velthuizen, H. T.; Verelst, L.; Wiberg, D. 2008. Global Agro-ecological Zones Assessment for Agriculture (GAEZ 2008). IIASA, Laxenburg, Austria and FAO, Rome, Italy.

Hersbach, H.; Bell, B.; Berrisford, P.; Biavati, G.; Horányi, A.; Muñoz Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Rozum, I.; Schepers, D.; Simmons, A.; Soci, C.; Dee, D.; Thépaut, J-N. 2018. ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Accessed January 2020, 10.24381/cds.adbb2d47

Huffman, G.J.; Stocker, E.F.; Bolvin, D.T.; Nelkin, E.J.; Tan, J. 2019. GPM IMERG Final Precipitation L3 1 day 0.1 degree x 0.1 degree V06, Edited by Andrey Savtchenko, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Accessed: January 2020, 10.5067/GPM/IMERGDF/DAY/06.

Mackay, J. D.; Jackson, C. R.; Wang, L. 2014a. AquiMod user manual (v1.0); British Geological Survey: Nottingham, UK.

Mackay, J. D.; Jackson, C. R.; Wang, L. 2014b. Environmental Modelling & Software, 61, 229-245. https://doi.org/10.1016/j.envsoft.2014.06.003.

Prudhomme, C.; Hannaford, J.; Harrigan, S.; Boorman, D.; Knight, J.; Bell, V.; Jackson, C.; Svensson, C.; Parry, S.; Bachiller-Jareno, N.; Davies, H.; Davis, R.; Mackay, J.; McKenzie, A.; Rudd, A.; Smith, K.; Bloomfield, J.; Ward, R.; Jenkins, A. 2017. Hydrological Outlook UK: an operational streamflow and groundwater level forecasting system at monthly to seasonal time scales. Hydrological Sciences Journal, 62 (16), 2753-2768. https://doi.org/10.1080/02626667.2017.1395032.

Sheffield, J.; Goteti, G.; Wood, E. F. 2006. Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling, Journal of Climate, 19 (13), 3088-3111. https://doi.org/10.1175/JCLI3790.1.

Tropical Rainfall Measuring Mission (TRMM). 2011/ TRMM (TMPA) Rainfall Estimate L3 3 hour 0.25 degree x 0.25 degree V7, Greenbelt, MD, Goddard Earth Sciences Data and Information Services Center (GES DISC), Data accessed: January 2020, 10.5067/TRMM/TMPA/3H/7.

Williams, A., Bloomfield, J., Griffiths, K., and Butler, A.; Characterising the vertical variations in hydraulic conductivity within the Chalk aquifer. Journal of Hydrology, 330, 53-62, 2006. https://doi.org/10.1016/j.jhydrol.2006.04.036.

Yatagai, A.; Kamiguchi, K.; Arakawa, O.; Hamada, A.; Yasutomi, N.; Kitoh, A. 2012. APHRODITE: Constructing a Long-Term Daily Gridded Precipitation Dataset for Asia Based on a Dense Network of Rain Gauges. Bulletin of the American Meteorological Society, 93 (9), 1401-1415. https://doi.org/10.1175/BAMS-D-11-00122.1.

Appendix 1

PAGASA METEOROLOGICAL STATIONS

Figure 8 shows the location of the 12 PAGASA meteorological stations used as part of the analysis of the gridded rainfall data.

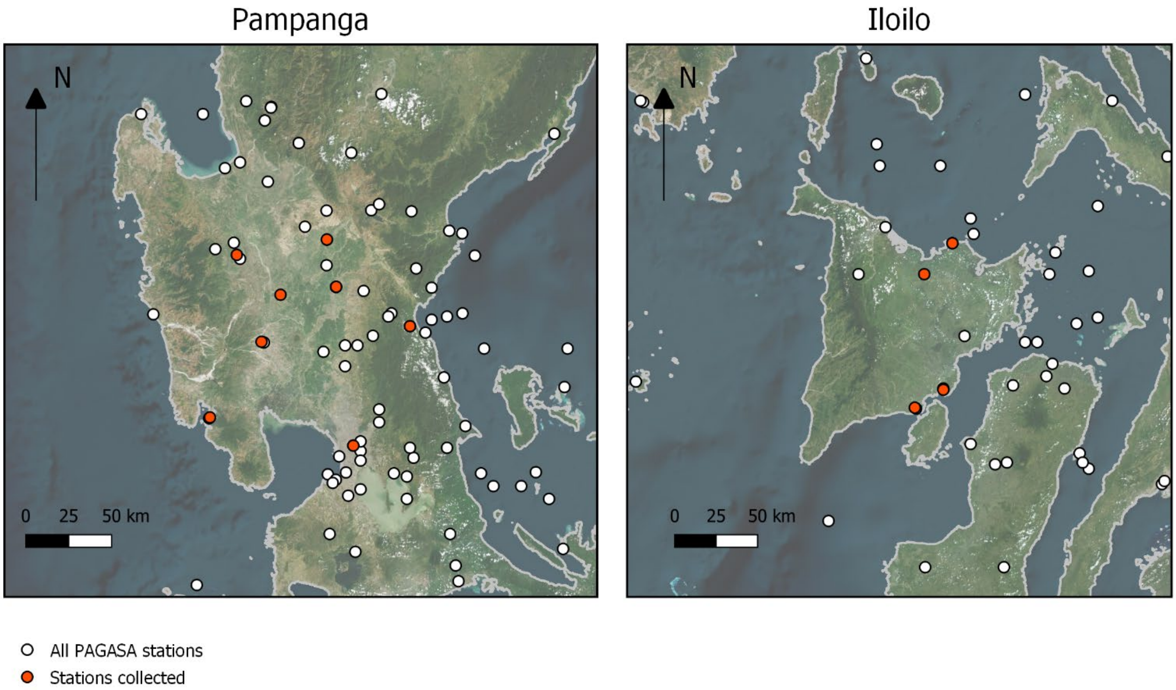


Figure 8: PAGASA meteorological stations used as part of the gridded rainfall data analysis for Pampanga and Iloilo. All stations highlighted in red were used. Imagery ©2022 Maxar Technologies, Google, Imagery ©2022 TerraMetrics, Map Data ©2022.