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Commonwealth Edison Company Flood Resilience – Technology for Response

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SUMMARY
Global concerns about flooding continue to increase, particularly given climate change considerations in our recent history. For Illinois spring precipitation is expected to increase 10%-20% by the year 2050, extreme precipitation events are also projected to increase, which may increase the frequency and magnitude of floods[1]. Multiple solutions have been proposed to mitigate interruption of electric distribution due to flooding, such as flood walls[2], equipment that can remain live in submerged conditions[3], and flood forecasting.

Delivery of flood forecasting solutions providing real-time advance warning to mitigate these concerns has been a goal of governmental, academic and engineering communities for some time. Cooperative efforts of these communities have seen various successful implementations at the state or federal government scale[4, 5]. Although successful, these implementations have limitations and do not often translate well to the local level where flood damages occur, either due to inadequate understanding by the end user or inadequate dissemination of helpful forecasting information to the end user.

The end result of this situation has been continued flooding of important life-sustaining or critical infrastructure energy distribution facilities. In order to mitigate for this situation and increase flood resilience, Commonwealth Edison Company (ComEd)/Exelon is partnering with watershed engineering specialists and software developers to implement a flood forecasting system providing advance warning of potential flood events at the local or site-specific scale.

During the past decade, ComEd has experienced damage to facilities and equipment from numerous severe flood events. This cumulative flood impact has translated into prolonged power service interruption for many customers and critical infrastructure, such as a large single high rise commercial customer near the Chicago River. This customer lost power for approximately one week in May 2020 due to a flooded basement substation. In this case,

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costs were incurred to repair and replace ComEd equipment, and flood damages occurred to basements and properties that relied on the basement substation power for sump pumps to maintain operational status. ComEd is addressing the flooding of important life-sustaining facilities or critical energy infrastructure through their resilience program which incorporates implementation of technology providing advance warning of potential flooding events.

ComEd selected a flood forecasting solution for their resilience program which integrates weather forecast and storm event data with watershed analysis as an emerging technology to forecast flooding risk at certain substation locations up to 48 hours in advance of significant storm events. The system forecasts flooding potential by analyzing publicly available weather, flood elevation, precipitation gauge data and data from sensors at substations sites and surrounding bodies of water.

The flood forecasting system continuously tracks larger magnitude storms in real time and performs watershed analyzes to determine approximate peak flood elevations and anticipated flood wave timing. For larger magnitude storms a flooding risk level assignment is made and advance warning alerts are communicated to emergency operations and control teams by Short Message Service (SMS) and email. This direct communication from the flood forecasting system allows improved ComEd response to potentially damaging storms and increased efficiency of ComEd personnel for proactive flood prevention, leading to reduced flood damage potential and increased flood resilience.

This paper will discuss the flood forecasting system in detail and illustrate benefits for emergency flood response provided by this emerging technology.

KEYWORDS
Flood, Forecasting, Resilience, Technology, Proactive Response, Storm Tracking, Climate Change, Substation

Global concerns about flooding continue to increase, particularly given climate change considerations in our recent history. For Illinois, spring precipitation is expected to increase 10%-20% by the year 2050, extreme precipitation events are also projected to increase, which may increase the frequency and magnitude of floods[1]. Multiple solutions have been proposed to mitigate interruption of electric distribution due to flooding, such as flood walls[2], equipment that can remain live in submerged conditions[3], and flood forecasting.

Delivery of flood forecasting solutions providing real-time advance warning to mitigate these concerns has been a goal of governmental, academic and engineering communities for some time. Cooperative efforts of these communities have seen various successful implementations at the well-funded state or federal government scale[4, 5]. Although successful, these implementations have limitations and do not often translate well to the local level where flood damages occur, either due to inadequate understanding by the end user (individual or entity directly impacted by the flooding event) or inadequate dissemination of helpful forecasting information to the end user.

The end result of this situation has been continued flooding of important life-sustaining or critical infrastructure energy distribution facilities. In order to mitigate for this situation and increase flood resilience, ComEd/Exelon is partnering with watershed engineering specialists and software developers to implement a flood forecasting system providing advance warning of potential flood events at the local or site-specific scale where the end user ultimately lives.

During the past decade, ComEd has experienced damage to facilities and equipment from numerous severe flood events. Although flooding impacts from severe storms extend well back in time, special attention began to be applied to mitigating flood damages in Northern Illinois and improving resilience after nearly back-to-back extreme flood years of 2008 (cost of flood damage and fatalities unknown), 2011 ($8M in flood damage, 0 fatalities) and 2013 ($375M in flood damage, 1 fatality)[6]. These flood damages have translated into prolonged power service interruption for many customers and critical infrastructure including an international airport, a major metropolitan business core and tens of thousands of residential and commercial customers.

As flood impacts appeared to continue to escalate, likely due in part to climate change activity, even more significant losses were just a matter of time, such that in May 2020 a severe flood impacted a large commercial customer high rise in the downtown Chicago Loop (Illinois, USA). This high rise lost power for approximately one week in May 2020 due to a flooded basement substation. Through all of these flooding events over the past two decades, costs to repair and replace ComEd equipment impacted bottom line expenses, and basements and properties that rely on electrical power for sump pumps or other operational equipment experienced flood damages, lost revenue or equipment failure.

To address these losses and impacts to customers and make significant strides to increased flood resilience, ComEd developed a flood risk prioritization matrix to classify over 800 substations and rank each for its key capacity of maintaining power during storm events. Rankings were based on service customer and site-specific characteristics such as critical infrastructure, number and type of customers served, depth of flood inundation, time to respond for power restoration or equipment protection and various other criteria. Through this evaluation it was determined that 31 substations in the grid network where a flood could create a significant impact and needed improved protection through implementation of flood prevention measures.

The selected flood prevention measures included 1) hard armoring with flood walls or 2) flood forecasting technology with proactive deployment of temporary emergency barriers. Decisions for hard armoring versus flood forecasting were based on total depth of flooding (FEMA FIRM Panels[7]), time required to raise temporary barriers (length/height of protection) and feasibility of flood protection within each substation (space constraints). ComEd chose the most severely flooded, and those which serve critical infrastructure, to be protected with flood walls. Given the high cost of implementing flood walls within each substation, ComEd will protect the remaining substations with flood forecasting technology or flood walls. This flood forecasting technology reduces operating costs of substations, and ultimately reduces customer costs, while still allowing for efficient emergency deployment of temporary barriers in advance of a potential flood event (at the time of publication, a total of five substations have been equipped with the flood forecasting technology). The remainder of this paper will be dedicated to describing that flood forecasting technology and demonstrating its benefits to ComEd.

In Northern Illinois, there is sparse near real time flood forecasting data for ComEd to use as emergency preparation at critical energy distribution locations. To address this gap, ComEd selected a flood forecasting system as an emerging technology which integrates forecast and real-time storm event data with watershed analyzes to forecast flooding risk at certain site-specific locations up to 48 hours in advance of large magnitude storm events (forecasted events with 2 inches or more of rain). The system forecasts flooding potential by analyzing publicly available flood elevation and precipitation gage data from local, state and federal sources including weather data from the National Oceanic and Atmospheric Administration (NOAA)[8], and USGS Current Water Data for the Nation[9]. In addition to publicly available data, the system integrates real time data from specific points of interest in the substation as well as water level data at bodies of water near the protected substations.

At each flood forecasting system deployed location, the system continuously tracks storm event changes for larger magnitude storms in real-time and performs watershed analyzes every fifteen minutes to determine approximate peak flood elevations and anticipated flood wave timing

The first step in this process is to determine which events should be analyzed for risk of flooding. The events are selected based on a two (2) inch threshold forecast rainfall depth with the understanding that the forecast rainfall depth could increase or decrease. On most days no significant rainfall occurs, and no evaluation is necessary. Each site has different parameters being evaluated once the forecast analysis is triggered, including a minimum 48-hour outlook forecast rainfall depth, previous real-time rainfall (as an estimation of current ground saturation levels), and current and forecast elevations of surrounding bodies of water.

During a large magnitude storm event for which the trigger has occurred, the flood forecasting system searches the publicly available data sources mentioned above every 15 minutes to update weather and stream gage information, which are critical inputs to perform the watershed analysis and forecast basic potential peak flood elevations with anticipated flood wave timing. The goal of the flood forecasting system is to provide flood peak elevations within six (6) inches of the actual peak and associated timing of the flood wave peak within six (6) hours of the actual peak. Achievement of these goals assists the ComEd emergency personnel by allowing them to prioritize emergency response at each substation based on when the flood peak is anticipated and how deep the potential flood inundation could be at each substation. In order to accomplish these forecast goals, detailed watershed analysis is required to develop a full understanding of the flooding source. An example of how this forecasting evaluation unfolds real-time to provide basic alert information consistent with the above stated goals and for emergency response, given variable forecast rainfall, is provided in a later section below.

The flood forecasting system applies tailored hydrologic and hydraulic engineering techniques to develop the necessary site-specific forecast information. The hydrologic engineering techniques are based on land use cover, land slope, antecedent moisture conditions, snowpack, and many other factors which may affect the amount of storm runoff. In the real world, commonly used simplifying assumptions are often difficult to integrate because, for example, a significant amount of rainfall following a dry period may have no effect on an at-risk substation, whereas a significant amount of rainfall following a wet period may generate critical flood elevations. ComEd looks at 30 days prior to forecast rainfall events to determine above or below average prior rainfall for estimation of potential ground saturation levels. Each hydrologic factor has an impact on the likely runoff and discharge within a waterway.

Hydraulic engineering techniques are based on waterbody geometry, waterbody resistance or obstructive characteristics, and proximity of the waterbody to the substation, including associated tailwater influences from other waterbodies. All relevant watershed conditions must be evaluated and included in the flood forecasting system analysis procedure in order to achieve the stated goals of plus or minus six (6) inches for a peak elevation forecast tolerance and a peak timing tolerance of plus or minus six (6) hours. This requires robust data mining, data storage and analysis methodology in order to operate without human intervention every fifteen (15) minutes during a large magnitude storm event.

During a large magnitude storm event the flood forecasting system evaluates the forecasted peak flood elevation every fifteen (15) minutes to track shifts in storm intensity and location. A dashboard is provided displaying relevant storm information, past rainfall depth, future forecasted rainfall depth and forecasted peak flood elevation and timing of the flood wave peak. An ongoing flooding risk level assignment is made and advance warning alerts are communicated to emergency operations and control teams by Short Message Service (SMS) and email. These alerts and the detailed data provide timely information for appropriate and adaptive response in the face of a flood event. This direct communication from the flood forecasting system allows improved ComEd response to potentially damaging storms and increased efficiency of ComEd personnel for proactive flood prevention, leading to reduced flood damage potential and increased flood resilience. ComEd also uses the alerts from the system to communicate forecasted flooding in customer buildings, as well as communicate flooding to a limited number of municipal sheriff's departments.

ComEd has deployed flood forecasting stations at five of its Northern Illinois facilities and plans to add more installations in the next five years. Each installation includes a custom-tailored solution for each site-specific watershed and management need involving:

- Onsite, real-time weather and stream gauge sensors,
- Remote telemetry,
- Acquisition of weather data from federal, state and local monitoring sites,
- Acquisition of federal, research-based weather forecasting data for the drainage basin out to 72 hours,
- Acquisition of federal stream gauge monitoring data within the site's drainage basin and adjacent basins,
- Redundant, cloud-based servers for data processing and storage,
- Mobile and desktop browser-based dashboard with user roles, and
- Custom triggers for SMS and email alerts based on observed and forecast conditions.

Storm Event Forecast Window Display

As mentioned above, the May 2020 storm event produced significant rainfall across the Chicago, Illinois (USA) metropolitan and suburban areas. The storm illustrates the condition that small rainfall amounts (3.6 inches over a 24-hour period, corresponding to a 2-year magnitude event) with antecedent moisture can result in dramatic results. It is likely that the groundwater table for this region was saturated from the significant rains in mid to late April 2020 prior to the May 14 and May 17 rainfall (two distinct groupings of rain).

To illustrate the performance of the flood forecasting system, forecasting results are provided below for review showing the system graphical outputs as they occurred during a May 2020 storm event at a ComEd substation.

The dashboard display for the ComEd substation for the May 2020 storm event is provided below as **Figures 1** through **4** giving a series of forecast "snapshots" taken during the storm event. On the left of the figures, the black columns along the bottom show actual rainfall in inches per hour. The blue shaded region shows the water elevation of the nearby body of water at each hour. The horizontal green dotted line shows the lowest elevation on the substation property. The horizontal orange dotted line shows the channel overtops (water height at which the stream will overtop its banks). The red horizontal dotted line shows the trough entry height at the control building. The other horizontal red dotted line shows the elevation of the lowest equipment foundation in the station. The horizontal green solid line shows the current hour, or “Zero” hour bar, splitting the real-time and forecast information, to the left of this line is actual rainfall or water height, to the right of the green solid line is forecasted rainfall and forecasted water height. The forecasted rainfall resides on the bottom right and is in shaded blue columns. The forecasted flood peak level resides on the top right.

Figure 1 below represents a snapshot at 1 pm on the afternoon of May 14 with a rain forecast of 2.07 inches, and flood forecast indicating a flood peak level just below the channel overtopping elevation with a flood peak time of about 7 am on May 15.

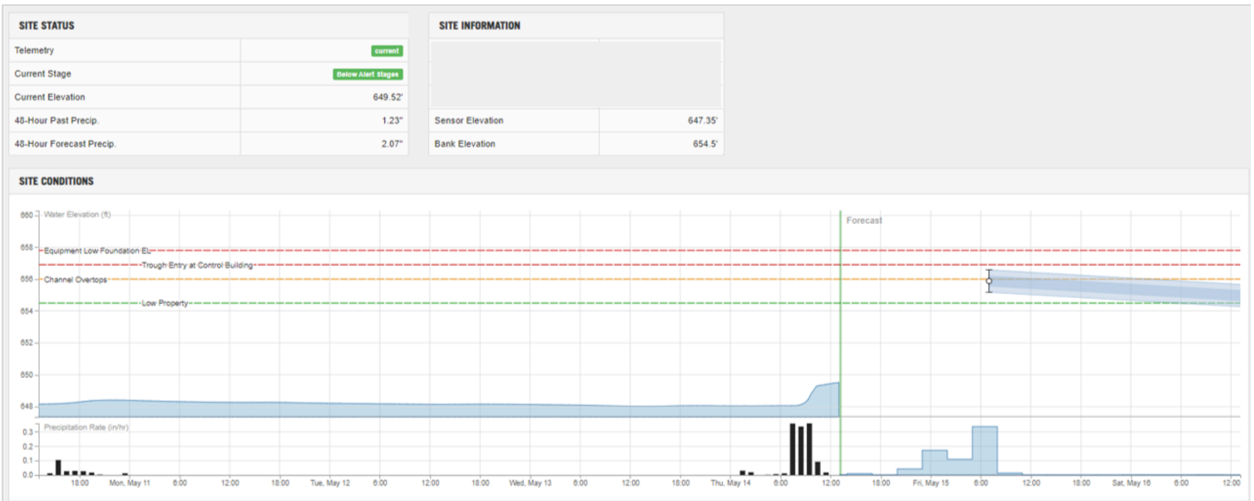


Figure 1: Forecast at 5/14/2020 1:00 p.m. (Past Rainfall = 1.23”, Forecast Rainfall = 2.07”)

Figure 2 below represents a snapshot of the real-time stream hydrograph on May 15 at 2pm. Notice the actual rainfall on Thursday May 14 corresponding to the water height increase of 3ft (648ft-651ft), and the rainfall on May 15 corresponding to another water height increase of 4ft (651ft-655ft) resulting in an actual flood peak timing of about 5 am on May 15 and a flood peak elevation about nine (9) inches lower than forecast.

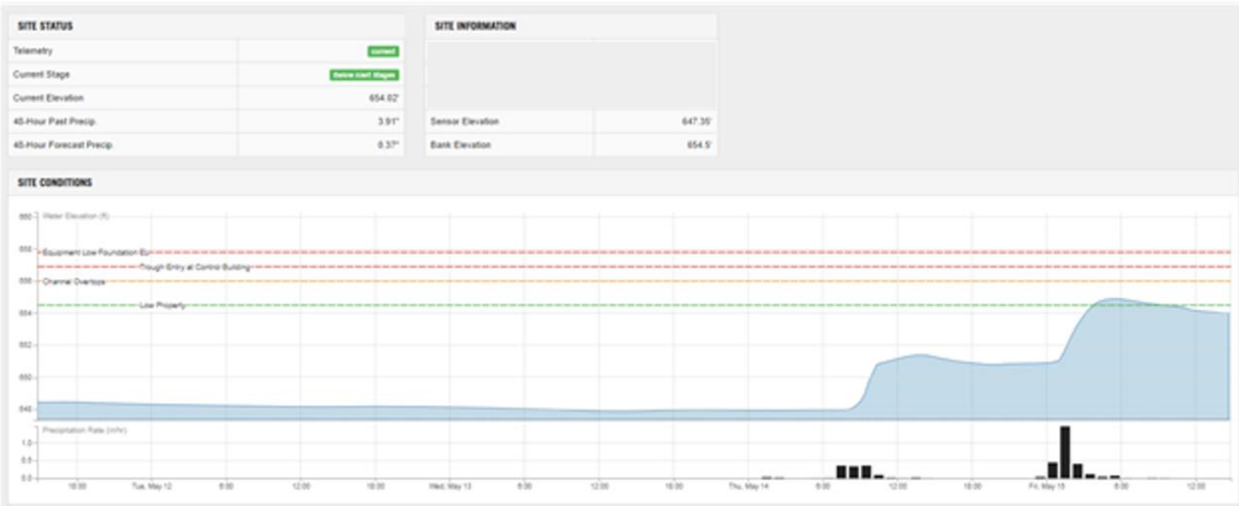


Figure 2: Snapshot at 5/15/2020 2:00 p.m. (Past Rainfall = 3.91”, Forecast Rainfall = 0.37”)

The storm progressed and another large magnitude storm was forecast just two days later on May 17. **Figure 3** below represents a snapshot at 9:45 am on the morning of May 17. Note the flooding source was elevated to 654ft, almost flooding the low property line in advance of this second grouping of forecasted rain. This elevated stream condition and the high antecedent moisture condition led to a higher likelihood of flood damage associated with the May 17 storm event. Figure 3 shows a forecast indicating a flood peak elevation just below a control building trough entry level but above the channel overtopping elevation with a flood peak arrival time of about 9 pm May 17.

ComEd substation engineering and regional management personnel were alerted and actively prepared for flood response at the substation during the storm event.

Figure 3: Forecast at 5/17/2020 9:45 a.m. (Past Rainfall = 1.09", Forecast Rainfall = 3.11")

Figure 4 below represents a snapshot of the real-time stream hydrograph subsequent to the May 17 rainfall event. Notice the actual rainfall spread out along the forecast grouping having a lesser depth of 3.2 inches instead of a forecast depth of 4.2 inches, resulting in an actual flood peak timing of about 11:30 pm on May 17 and a flood peak elevation about 6 inches lower than forecast.

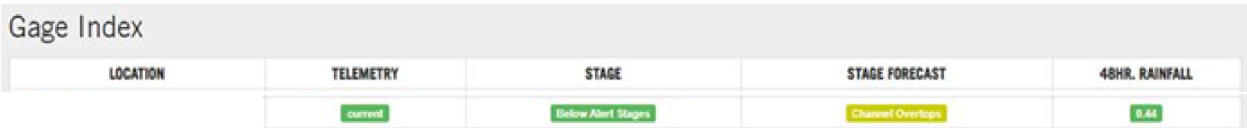
Figure 4: Snapshot at 5/18/2020 7:00 a.m. (Past Rainfall = 3.14", Forecast Rainfall = 0.10")

Storm Event Forecast Alert Panel

The May 2020 event above illustrates the forecast results storm event hydrograph output. A June 2021 storm was selected to illustrate the separate dashboard Alert panel graphic. The Alert panel provides a simple explanation estimation of risk for a particular storm event at a particular time during the storm event. The risk estimation varies depending on the site equipment or building characteristics and the changing nature of publicly available forecast input. With respect to alert dissemination, the June 2021 storm shows the changing nature of the alerts to ComEd personnel. **Figures 5** and **6** show this dynamic alert situation allowing for adaptability and efficiency as a given storm progresses. The alert images show current flooding information in column 2, “STAGE”. Column 3 shows “STAGE FORECAST” which is the alert type for the substation forecasted, the forecast can be below alert stages, or the alert will correspond with the height of the forecast, such as “Low Property” (corresponding to the green dashed line on figures 1-4).

. The initial public forecast rainfall depth of the June 2021 storm was approximately 9 inches, for a summer storm on this watershed, would be well above a 100-year magnitude storm. The significant alert levels resulted in an immediate review of the alerts being broadcast by a ComEd task force responsible for tracking this potential flooding event. Ongoing review of the forecast data for continued updates to ComEd personnel were provided by the flood forecasting system to the ComEd task force every 3 hours for additional review and emergency response adjustment. The first cloud wave of this storm event ended up moving south of the ComEd service area and the rainfall forecasted for that initial cloud wave did not contribute to flooding. Within a few hours the public forecast rainfall depths had dropped significantly so by afternoon hour the forecast was almost half the original forecast rainfall, but still indicated potential risk to the site.

Figure 5 below represents alerts issued for the publicly available rainfall forecast, which indicated an additional 5.3 inches of forecast rainfall, which would be added to the 0.44 inches of 48-hour past (morning) rainfall shown on the screen capture graphic.


Gage Index

LOCATION	TELEMETRY	STAGE	STAGE FORECAST	48HR. RAINFALL
	current	Below Alert Stages	Channel Overtops	0.44

Figure 5: Snapshot of Alert Panel for Site Location about 3 pm on June 24, 2021

Figure 6 below represents alerts issued for rainfall the publicly available rainfall forecast, which indicated an additional 3.7 inches of forecast rainfall, which would be added to the 0.44 inches of 48-hour past (morning) rainfall shown on the screen capture graphic (for rainfall forecast to occur about 12 hours in the future). The actual or real-time rainfall amount for this event turned out to be about 3 to 4 inches of rainfall over a 48-hour period.


Gage Index

LOCATION	TELEMETRY	STAGE	STAGE FORECAST	48HR. RAINFALL
	current	Below Alert Stages	Low Property	0.44

Figure 6: Snapshot of Alert Panel for Site Location about 4 pm on June 24, 2021

Ongoing Improvements

The flood forecasting system is updated for clarity of communication and increasing robustness as issues arise. Site specific redundancies are incorporated in the evaluation process to exclude or replace bad and/or non-reporting data from public sites. Individual site results are reviewed for compliance with the performance goals described above with design changes being implemented to improve accuracy of forecasting results. Also, on-going technology improvements and analysis techniques are evaluated for potential incorporation into the flood forecasting system to increase reliability and accuracy. Examples of analyzes techniques under consideration to improve accuracy include Monte Carlo simulations, automated neural networks and artificial intelligence for continuous learning.

Additionally, ComEd could use past storm data to track changes in flooding risk as rain patterns change. If specific stations are receiving more flood warnings than in pervious years, ComEd could make a decision to upgrade a system from software flood protection to hard armouring via flood walls at that substation.

The flood forecasting system could also be used to enhance customer safety. The flood forecasting could be shared directly with customers, via a local municipal contact, sheriff's departments, or directly with large customers. Municipalities may benefit from seeing this flood forecasting data to prepare for flood events and keep residents safe. Large customers could deploy their own flood response measures to protect equipment.

In summary, the flood forecasting system assists ComEd in managing flood risk for critical and vulnerable operational sites which supply power to local residential and business customers. The flood forecasting system communicates directly with emergency operations and controls teams to improve ComEd response to storms and to increase efficiency of ComEd personnel for proactive flood prevention, rather than reactive damage control. ComEd's adoption of this emerging technology provides an opportunity to reduce flood damage potential and increase flood resilience for this Northern Illinois region.

BIBLIOGRAPHY

[1] Frankson, R., K. Kunkel, S. Champion, B. Stewart, D. Easterling, B. Hall, and J. R. Angel, 2017: Illinois State Climate Summary. NOAA Technical Report NESDIS 149-IL, 4 pp.

[2] Rising to the occasion of substation flood protection. Concrete Products, [s. l.], v. 74, n. 1, p. 64, 2021. Disponível em: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=bsu&AN=148102908&site=ehost-live&scope=site. Acesso em: 11 jan. 2022.

[3] AMIR, M. D. M.; ISHAK, S.; GOPAL, A. R. Design and Evaluation of Submersible 11/0.415kV Distribution Substation for Flood Prone Areas. Telkomnika, [s. l.], v. 15, n. 4, p. 1540–1546, 2017. DOI 10.12928/TELKOMNIKA.v15i4.7232. Disponível em: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=asn&AN=127677036&site=ehost-live&scope=site. Acesso em: 11 Jan. 2022.

[4] BUAHIN, C. A. et al. Probabilistic Flood Inundation Forecasting Using Rating Curve Libraries. Journal of the American Water Resources Association, [s. l.], v. 53, n. 2, p. 300–315, 2017. DOI 10.1111/1752-1688.12500. Disponível em: https://search.ebscohost.com/login.aspx?direct=true&AuthType=ip,shib&db=asn&AN=122272917&site=ehost-live&scope=site. Acesso em: 12 jan. 2022.

[5] Cicily Kurian, K.P. Sudheer, Vamsi Krishna Vema, Debabrata Sahoo, Effective flood forecasting at higher lead times through hybrid modelling framework, Journal of Hydrology, Volume 587, 2020, 124945, ISSN 0022-1694, https://doi.org/10.1016/j.jhydrol.2020.124945. (https://www.sciencedirect.com/science/article/pii/S0022169420304054)

[6] National Weather Service, National Oceanic and Atmospheric Administration, Flooding in Illinois, Significant Illinois Floods, https://www.weather.gov/safety/flood-states-il

[7] Federal Emergency Management Agency, FEMA Flood Map Service Center, https://msc.fema.gov/portal/home

[8] National Weather Service, National Oceanic and Atmospheric Administration, Forecast Maps, https://www.weather.gov/forecastmaps

[9] US Department of the Interior, US Geologic Survey, USGS Current Water Data for the Nation, https://waterdata.usgs.gov/nwis/rt