ELECTRIC POWER RESEARCH INSTITUTE

Determining the Optimal Locations for Weather Sensors in a Mesonet

The Mesonet Design Algorithm

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ABSTRACT

The QuantumWeather® proprietary mesonet placement algorithm was applied to solve the problem of deciding the specific location of multi-parameter weather sensors, designed for two distinctly separate mesonets. Each mesonet placement addressed unique environmental characteristics such as different weather histories, differing topographies, and distinct weather forecast challenges. Each mesonet design also took into consideration the unique response requirements and challenges of each utility company. Three mesonet design options are proposed, from highest to lowest forecast performance of sensor deployment.

Keywords

Weather prediction
Mesonet
Damage prediction
Weather sensor

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1 INTRODUCTION

Since the 19th century, electric utilities have relied on weather forecasts to inform their preparedness for weather events that could cause power interruptions, damage to field assets, and peril to work crews. Advances in meteorology and improvements in the reliability of weather forecasts over the past few centuries have followed advances in technology, from the weather lore of ancient people using their physical senses to recognize atmospheric patterns wherever they happened to be to modern planetary eavesdropping using advanced satellites, radar, and ground-based mesoscale networks of weather stations called *mesonets.*

This document discusses tailoring mesonets to the service territory of two particular electric utilities to increase the reliability of weather forecasts with enough lead time to enable them to deploy assets, stage line crews, and ready itself for weather to come. The document focuses on the proprietary siting algorithm of Saint Louis University's QuantumWeather®, which enables optimal placement of weather stations in a mesonet, which requires considerable precision and accuracy of the initial values that seed a mesoscale weather-forecasting computer model. Such an improved mesonet would enhance the ability of electric utilities to both anticipate and react to detrimental weather events, thereby improving customer reliability.

Better initial values for a computer model for weather and damage prediction begin with conversations with the electric utility to tailor a mesonet to its idiosyncratic needs, the unique nature of its service territory, and the types of weather-related phenomena that need to be predicted and accounted for, such as wind and accumulation of snow and ice. Combined with superior data from a tailored mesonet, the QuantumWeather® system represents the next evolutionary phase in weather forecasting for electric utilities.

For an introduction to QuantumWeather® and its genesis, please read Ameren Missouri Tackles Storm Forecasting to Anticipate System Damage and Accelerate Restoration of Service. EPRI, Palo Alto, CA: 2015. 3002006638.

2
THE VALUE OF MESONETS TO ELECTRIC UTILITIES

When properly configured and consisting of sufficient weather sensor stations, mesonets can provide highly precise and accurate data to a computer model. When fortified with such data, a weather- and damage-forecasting model can positively inform utility decisions to commit assets and deploy crews, when and where to stage assets, and when to ask for mutual aid prior to an imminent weather event.

A mesonet feeding a forecasting model that is tailored for a particular service territory provides predictions that are far superior to commodity weather forecasts such as the National Weather Service (NWS), The Weather Channel (TWC), and AccuWeather. Such sources of weather forecasts are prone to false positives. That is, they may *suggest* deployment of assets when deployment is not necessary, to the wrong magnitude, or to incorrect locations. The mesonets described in this document can help prevent such false positives in addition to providing more accurate magnitude, type, duration, and timing of events.

The atmospheric conditions at a single weather station within a mesonet can be gathered frequently—such as once per minute—to ensure that the weather movements and patterns are accurately represented in the model. Data from a mesonet is quality controlled periodically—such as every five minutes. Quality-assurance tests are also conducted periodically to ensure that mesonet data is reliable. Reliability is further enhanced by periodic maintenance and calibration of the weather sensors.

With highly reliable data from a tailored mesonet, an electric utility can make decisions about preparation for power outages and restoration of power with far greater confidence, reducing the number of damaged assets, loss of revenue, overtime pay, and cleanup, as well as accelerating restoration time.

3

THE COMPOSITION OF THE QUANTUMWEATHER® MESOSCALE FORECASTING SYSTEM

The mesoscale-based forecasting system designed and developed by Saint Louis University (SLU) consists of a network of weather stations, enrichment data sources, and a meteorological computer model.

Multi-Parameter Mesonet Weather Stations

The backbone of the mesonet is a fleet of multi-parameter weather stations, such as the one shown in Figure 3-1. A mesonet weather station is arrayed with sensors to detect atmospheric conditions consequential to the reliable operation of electric utility assets, including temperature, humidity, atmospheric pressure, wind (speed and direction), and precipitation (rain, sleet, freezing rain, and snow).

Figure 3-1
A multi-parameter weather station

Network of Stations

In addition to the challenges of the optimal siting and installation of a weather station is interconnecting the fleet to form a timestamped network that feeds data to the computer model. The density of a network determines a model's predictive power, to some extent. Roughly speaking, a network with low spatial density—typically one station per county, similar to both the New York state and Oklahoma mesonets—can provide valuable yet usually sporadic information to aide in the initiation of a global model or to enhance special research experiments. However, they cannot reliably inform decisions made by electric utilities ahead of impending weather events.

Weather stations in the field must be able to communicate their parameter values to the back-office operation of the utility or host system supporting the weather- and damage-prediction system. Any existing, reliable communication protocol can be leveraged over a communication backbone, depending on the best method available, such as SCADA, cellular, or private radio. The hardware communication protocol should be robust enough to support the mesonet under the stresses expected during adverse weather conditions. The communication backhaul system should ensure reliable support during outages to ensure continuity of service.

Under most conditions, a utility will attempt to locate a weather station close to its own utility network, such as near substations, power stations, sectionalizers, capacitor banks, and other networked intelligent devices with communication. The weather stations currently supported by the QuantumWeather® prediction model used by Ameren-Missouri (the Lufft WS600-UMB) supports the following protocols:

- Modbus-RTU
- Modbus-ASCII
- SDI-12
- XDR
- Terminal-Mode
- Binary

Other Data Sources

The QuantumWeather® system can achieve forecasts of higher resolution (as compared to a commodity forecast) by assimilating data from both a tailored mesonet and data from carefully sited radiosonde launches. A radiosonde is an instrument platform launched into the atmosphere (typically by a weather balloon) that measures ambient temperature, humidity, barometric pressure, and other atmospheric parameters at various altitudes and transmits the data by radio to a ground receiver.

Computer Modeling

Because the atmosphere is a fluid, it is subject to the laws of physics and fluid dynamics. Based on the equations of those fields, meteorologists can produce numerical weather predictions. However, “seeding” the equations with inaccurate numerical representations of current atmospheric conditions can render weather models less resolute.

When weather events historically prove disruptive to essential services—such as electricity—providers of those services require forecasts that are highly accurate for their service territories to evaluate hardening strategies that may reduce disruption of service, accelerate restoration of service when disruption occurs.

Today’s robust earth and atmospheric computer models use refined equations and accurate input data to render reliable forecasts. To ensure high accuracy for a given service territory, the QuantumWeather® computer model relies on seeding the model with precise and timely data, periodically gathering data from weather stations, updating whether forecasts based on newly gathered data, and refining the computer model based on how well it has predicted weather events along the timeline.

Initiation data for the prediction model falls into two meta-categories: spatial and temporal. Where is the data coming from and when was it collected? Properly initializing a model with current, precise atmospheric conditions is crucial to producing an accurate prediction. Therefore, the quality of the data sources that feed the model and the initial values must be precise and accurate, truly representative of the current conditions at that station's location.

4

CRITERIA FOR OPTIMAL PLACEMENT OF MESONET WEATHER STATIONS

Prudent siting of mesonet stations provide key information for more accurate forecast model initialization, which leads to a much more accurate forecast. The criteria for optimal placement of weather station sensors in a mesonet include the customer requirements, terrain and water bodies that affect weather, and the density of the stations required to render accurate forecasts. Electric utilities typically require forecast lead times in the range of four to 24 hours, with varying lead times depending upon the type of anticipated weather event. The main weather-related problems experienced by a utility also contribute to the placement of a weather station, such as wind or sensitivity to a certain type of precipitation. Utilities may also specify the emphasis of a forecast, such as rain volume, snow volume, or wind vector.

The density of a mesonet affects the probability of actionable intelligence. A low-density mesonet—one with a minimal number of weather stations per area—may not render data that is reliable enough to support the operational decisions of electric utilities. The number of weather stations per area include those that are arranged geometrically and those that are installed in "special" locations. A special location is one that provides data about crucial local terrains or climatological effects.

If physical limitations preclude siting a weather station at a location, it can be sited nearby without inducing major prediction errors as long as the relocation is less than one-half of the optimal grid-square bias (such as less than 35 km [~ 22 miles]) and as long as *many* stations are not moved from the desired locations.

Challenges to optimal placement of weather stations in a mesonet include:

- Bodies of water as obstacles
- Right-of-way access
- Isolated topography
- Structures affecting measurements
- Rough terrain
- Budget
- Communication limitations
- Channeling of weather events across a terrain, such as valleys and mountain passes
- Lake effects, such as wind and precipitation

Such challenges may require alternative siting of stations. The longer the lead time, the more alternative siting will affect the accuracy of forecasts.

5

QUANTUMWEATHER® AND THE MESONET DESIGN ALGORITHM

The purpose of a weather forecast directed to an electric utility is to alert the utility to a weather event with details on the conditions that could result in infrastructural damage and interruption of electricity to its customers. A "weather event" is:

- Driving and tornadic winds (which meteorologists call "convective events").
- Precipitation (rain, snow, sleet, freezing rain, and hail), or a combination thereof.

The results of such weather events include:

- Flooding
- Downed powerlines caused by wind or the accumulation of ice or snow on tree limbs and power lines
- Damage to electrical assets
- Power outages
- Exposure of electrical hazards to the public and work crews

SLU was originally contracted with Ameren to evaluate the algorithm they presently use to optimally site weather stations to enable the QuantumWeather® system to generate the most reliable and actionable forecasts possible. The algorithm is called the Mesonet Design Tool Chain. Using this algorithm results in a mesonet and computer model that are both tailored for a utility to yield higher resolution weather forecasts within the utility specified lead times.

The location of a mesonet and each weather station in it addresses unique environmental characteristics such as various weather histories (climatologies), topographies, and distinct weather forecast challenges. Each mesonet design also takes into consideration the response requirements and operational challenges of each utility company.

The Mesonet Design Tool Chain includes:

- A questionnaire regarding the utility's requirements and weather-related challenges.
- The required lead time, which depends in part on how far crews and assets must travel from home base to the staging area and the impediments to this travel.
- Historical storm climatology in the service territory.

With these three known, the size of the mesonet domain can be defined. Issues such as land-use and governmental restrictions on the location of the domain must also be addressed.

The spatial and temporal sensor resolution must be defined to capture the initial state of the atmosphere (establish a baseline) necessary to satisfy customer requirements. To accurately describe the temporal evolution and movement of a weather system, crucial points in the systems evolution need to be captured.

Nyquist sampling theory states that three to five samples of a wave are necessary to describe a wave's motion. This sampling applies both to the spatial as well as temporal scales. Also crucial to system evolution are terrain effects, elevation, and channeling effects. Thus, to adequately describe a weather system's temporal evolution, the mesonet domain needs to be large enough to document these effects. Finer grid spacing in the field and in the computer model helps capture modeled convective events as they evolve.

Finally, the Mesonet Design Tool Chain identifies "special" sites for weather stations, which provide information about the environment at locations crucial to solving the forecast problem for a particular area.

6
INSTRUCTIVE CASE STUDIES

Each mesonet placement addresses unique environmental characteristics and utility needs. Lead time, for example, is both a requirement and a challenge for forecasters. Sometimes, the optimal mesonet design (placement of multi-parameter weather stations) is not practical because of terrain or budget constraints, which requires fine-tuning of the prediction model.

Under contract to EPRI, SLU employed its Mesonet Design Tool Chain to produce three optional, tailored mesonet solutions to two electric utilities to support weather forecasting and damage-prediction models. Design-Option #1 was called the Optimal Level and had the highest density of weather stations in the custom mesonet. Design-Option #2 was called the Enhanced-Level and had moderate density. Design-Option #3 was called the Entry Level and had the lowest density.

The forecast lead-time provided to the QuantumWeather® team was defined to be the time frame needed for asset deployment. The enhanced-level and entry-level scenarios reduce areal coverage but maintain the spatial resolution to satisfy the 8- and 4-hour lead times, respectively. Factors that influence the lead-time are the distances that deployed assets must cover from home base to a staging area and any impediments that have to be considered in the deployment sequence (such as mountain terrain, limited access locations, and unimproved roads).

In the EPRI project, two utilities participated, providing enough data to employ the Mesonet Design Tool Chain: Appalachian Power, which is an operating company of American Electric Power (AEP) and Central Hudson Gas and Electric (Central Hudson). Although each service territory had its own idiosyncratic needs, both utilities were concerned with heavy, wet snow.

Case 1: Appalachian Power

Appalachian Power's service territory is much larger than Central Hudson's. Therefore, Appalachian Power also levied a much longer (but constant) forecast lead-time requirement of 24 hours. As with the Central Hudson design, the primary forecast concern was heavy, wet snow with a secondary concern for strong gusty winds from convective events. Given that the Appalachian Power service territory is much larger and adding the more rigorous requirement of a much longer lead-time, the resultant mesonet was significantly larger than that of Central Hudson.

Optimal-Level Design

In order to cover the larger domain with a lead time of 24 hours, the mesonet stations (in the Optimal-Level design) are spaced approximately 22 miles (~ 35 km) apart (noted as blue dots). Again, stations were also specifically sited to cover channeling and other topographic effects across the service territory (noted as red dots in the figures). Figure 6-1 shows the Optimal-Level design for the Appalachian Power service territory.

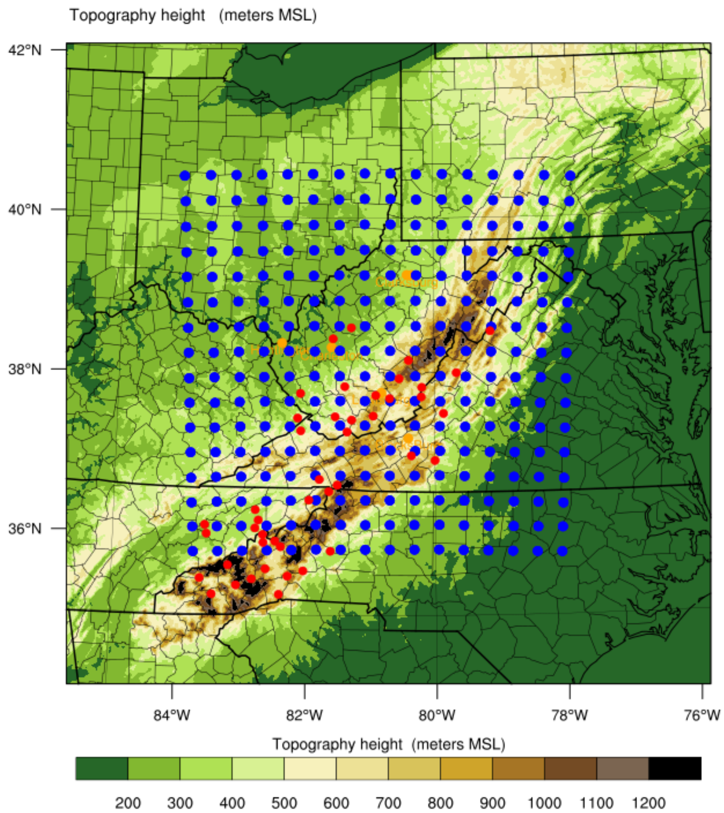

Figure 6-1
Optimal-Level design for the Appalachian Power service territory

Although any utility company has difficulty dealing with challenging weather, Appalachian Power could experience significant problems staging crews and gaining access to assets during and soon after certain hazardous weather events. Having a dense station spacing across the service area will help more quickly define which location(s) will be affected by a hazardous weather event. The stations need to report once a minute. Although the primary forecast problem of interest is still heavy, wet snow, the source of that snow varies from early winter to early spring. Northeasterly flows around strong wintertime storms moving along the east coast are also major watchers for hazardous weather events. Given this additional piece of information, the mesonet domain was optimized to include capturing multiple systems—Nor'easters and systems as they develop in north-central United States. Mesonet stations were also located to capture developing wintertime systems from the north-central United States. Those will capture developing convective systems in Illinois and Indiana.

Appalachian Power requires actionable intelligence on the rate of accumulation and totals of heavy, wet snow to fall during any specific winter weather event. It is a primary weather parameter because of how the heavy, wet snow affects the conifer trees that are common in their service territory. As a secondary concern, Appalachian Power needs to be cognizant of areas of possible damage from strong gusty winds emanating from convective events. Anticipating possible damage locations can alert decision makers of the possible need to send crews into areas difficult to access.

Upslope snowfall can be fed by ambient moisture already present in an air mass, the Great Lakes play a large role in many Appalachian upslope snow events by “loading” the air with moisture as winds pass over the surface of the water. The winds act as a conveyor belt, carrying the plume of lake moisture to the mountains, where it is then “squeezed out” in the form of rain or snow by upslope lift. In this way, many of Appalachian Power’s snow events are a type of lake-effect snow, even being far away from the actual lakes.

For the Appalachian Power case, there are two predominant sources of heavy, wet snow, each exhibiting a different developmental time line. In one scenario, the snow event is identifiable much earlier because it provides indications of a developing snow event on a large, regional weather scale. In the other scenario, that preferred storm track has fewer long-lead time indicators, and the storm also develops much more rapidly. The mesonet spatial configuration/resolution was designed to identify both possibilities.

Further, for Appalachian Power, the channeling of “weather” into valleys surrounded by high terrain may alter the model prediction based upon the spatial resolution of the mesonet sensors. The “special” sensors were placed to answer question of “if” and “how” will the topography and channeling effect change a rain event into a heavy, wet snow event? During the summer months, these “supplemental” stations are designed to determine whether differential heating on mountainsides will lead to the formation of a thunderstorm. Each design addresses a constant lead-time but different level of spatial resolution, based upon customer-specified requirements.

Enhanced-Level Design

The station spacing of the Enhanced-Level grid network is roughly 70 km (~ 43 miles) between sites, as shown in Figure 6-2. This pattern reduces the number of sensors by 28% from 300 to 216 (removed 112 grid point sited stations; kept 44 special sites => 216 sites remaining). This results in a less-than-optimal network. Fast-developing winter snow storms and summertime convective events will not be identified as quickly by the mesonet, and therefore the current in-situ weather initialization of the QuantumWeather® weather model will be slower and less precise in indicating where severe weather hazards may form. Again, the given lead-time requirement is maintained.

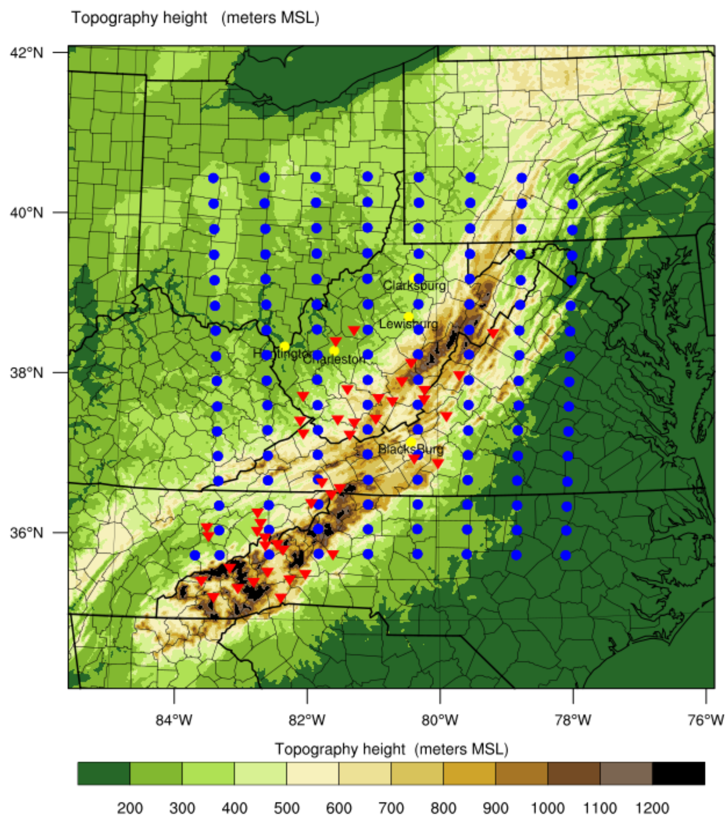

Figure 6-2
Enhanced-Level design for the Appalachian Power service territory

Entry-Level Design

The station spacing of the Entry-Level grid network is roughly 100 km (~ 61 miles) between sites, as shown in Figure 6-3. This pattern reduces even more the number of sensors by 66% from 300 to 85 (removed 215 grid point sited stations but kept 44 special sites => 129 sites remaining). This results in a network that is far less than optimal. Fast-developing winter snow storms and summertime convective events will be identified much more slowly or possibly not at all when compared to the Optimal- and Enhanced-Level station siting. This reduces even further the current in-situ weather initialization of the SLU weather model, which will be less precise and timely in indicating where severe weather hazards may form. Again, the given lead-time requirement is maintained.

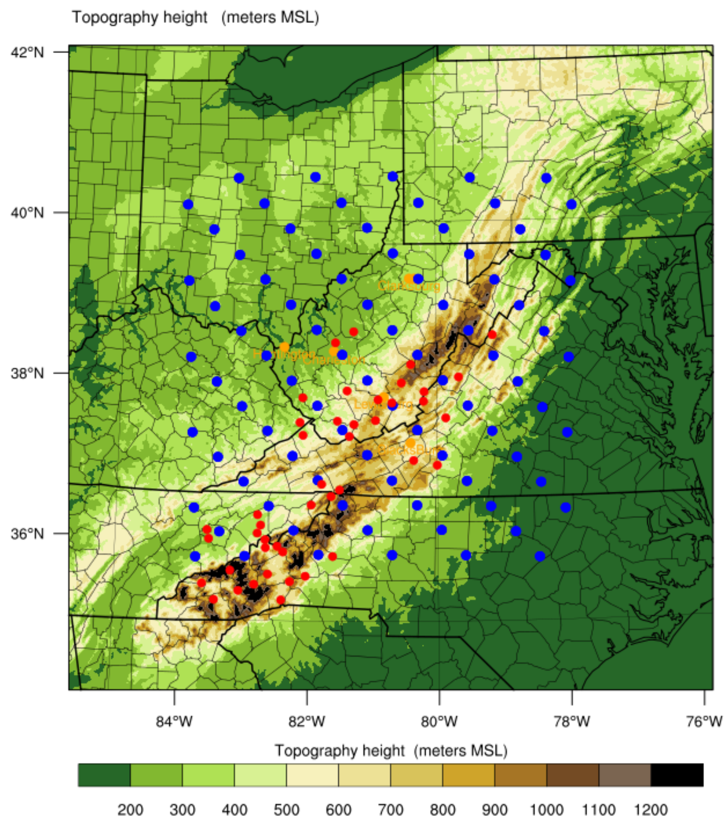

Figure 6-3
Entry-Level design for the Appalachian Power service territory

Case 2: Central Hudson

Central Hudson has a compact footprint, which lends itself to investigating various lead-time alternatives while maintaining a high-density mesonet. Central Hudson requested that the project focus primarily on a warning lead time of a very short 4 hours. Another request was to provide high accuracy time and location forecasts of hazardous weather events with a verification rate of 60% or greater.

As with Appalachian Power, the primarily forecast problem for Central Hudson is a cold-weather phenomena, specifically heavy, wet snow events. However, Central Hudson's lead-time requirement is much less formidable than is Appalachian Power's. A secondary concern is strong gusty winds from convective events. Note that some of the heaviest snow events are caused by convective storms imbedded within winter storms. Although there were no significant geographical impediments to crew deployment, the topography of the region still plays a significant role in meeting response times for forecasting timely hazardous weather events. Because there is a requirement for high-spatial and -temporal-resolution forecasts and due to the short lead time, there are weather stations that are closely spaced (average spacing is roughly 9.2 miles or 17 km). These stations will report once a minute.

Initial placement of weather stations took into consideration how to develop solutions to the Naiver-Stokes Equation for fluid flow at these scales of motion. Next, because the passage of Nor'easters and systems bring cold air across the Great Lakes and serve as primary sources of heavy, wet snow for this region, weather stations were sited to optimize information about lake-effect snow and coastal snowstorms. Because there is also a secondary risk of convective storms being channeled by topography, weather stations were also located to cover such channeling effects. The Optimal-Level design allows accurate forecasts of developing lake effect storms and convective events developing along the Great Lakes. The Enhanced Level and Entry Level configurations retain the close station spacing to ensure that forecast accuracy is kept as high as possible. However, because of the reduced areal coverage, temporal accuracy in the form of lead time correspondingly must decrease.

In the Central Hudson case, heavy snowfall events are the result of Nor'easters, long bands of lake-effect snow, and wet snow associated with moisture wrapping around decaying tropical storms. These summertime convective events often produce isolated wind gusts in the 50-mph range. The key issue in this case is the channeling of the storm's path due to the Adirondack and Catskill Mountains and the Mohawk River.

Optimal-Level Design

For Central Hudson, the sensor spacing of the Optimal-Level grid network is roughly 15 km (~9 miles) between sites, as shown in Figure 6-4. This pattern is designed to optimize the QuantumWeather® weather model initialization to provide the most precise prediction possible, given the lead-time requirement. The total number of sites includes 206 sites to optimize model initiation and include an additional 15 sites to address terrain-induced weather effects and 24 legacy sites. The most care should be taken to locate as precisely as possible the 15 “special” stations (see the red dots in Figure 6-4). The mesonet design in this case is design to provide between 12 and 18 hours of lead-time while preserving the highest forecast accuracy.

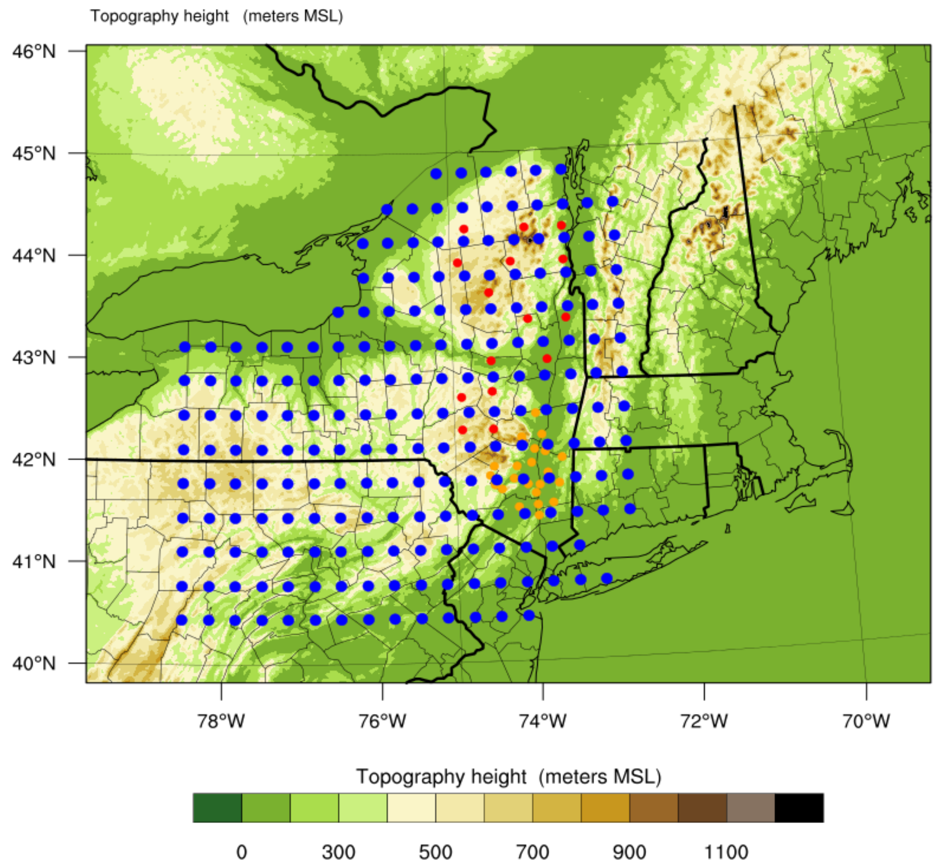

Figure 6-4
Optimal-Level design for the Central Hudson service territory

Enhanced-Level Design

The station spacing of the Enhanced-Level grid network is maintained at roughly 15 km (~9 miles) between sites, as shown in Figure 6-5. This pattern reduces the number of sensors by 27% from 206 to 150. In this case, the mesonet was designed to maintain the forecast accuracy while reducing the lead-time. The sensors at the outer edges of the domain have been removed. With sensors being removed from the outer edges of the domain, the ability of the mesonet to sense approaching systems and the development of convective events decreases.

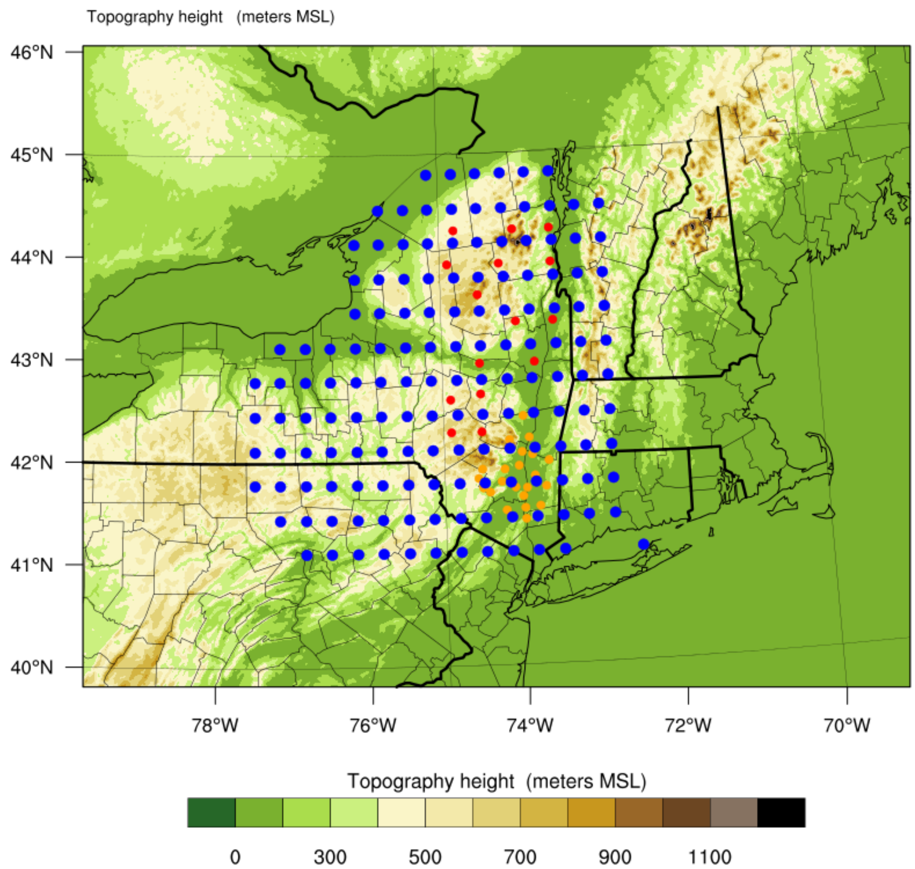

Figure 6-5
Enhanced-Level design for the Central Hudson service territory

Entry-Level Design

The station spacing of the Entry-Level grid network is roughly 15 km (~ 9+ miles) between sites, as shown in Figure 6-6. This pattern reduces even more the number of stations from 150 (functional) to 103 (removed 8 grid point sited stations but kept 15 special sites and 24 Legacy sites => 103 sites remaining). This mesonet design result in a network that is far less than optimal.

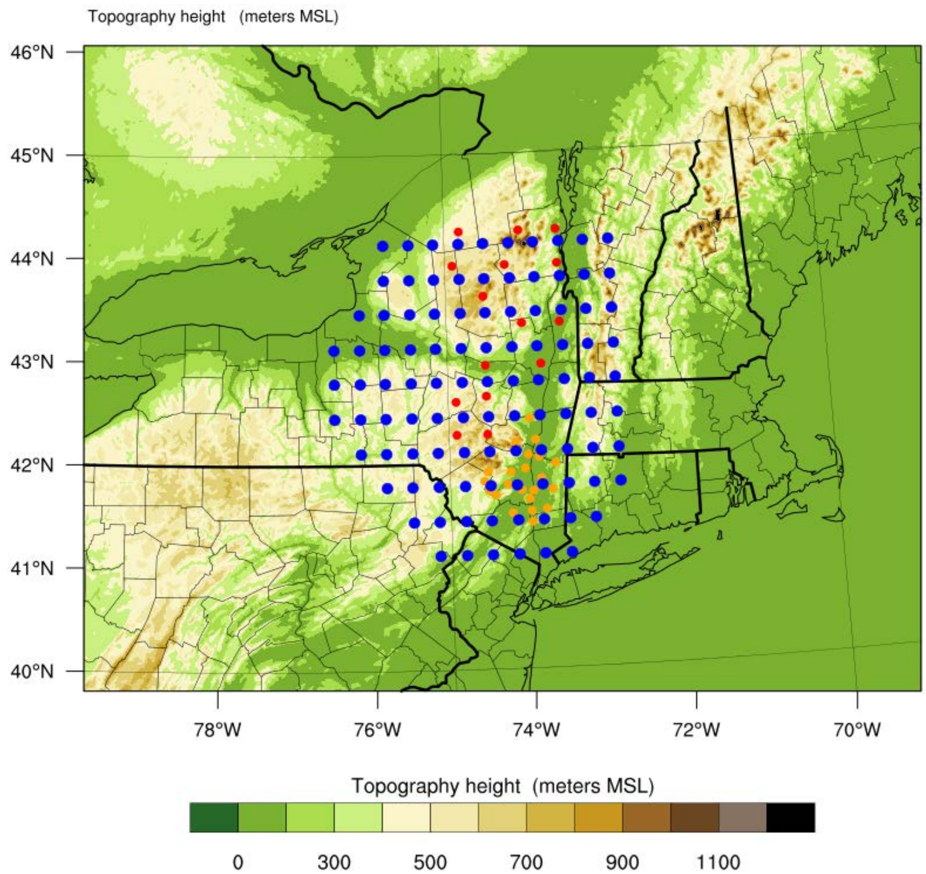

Figure 6-6
Entry-Level design for the Central Hudson service territory

7 CONCLUSION

Integration of forecast data with other data (such as GIS, vegetation location and health, land use, land cover, and disposition of work crews) will enable a snapshot of potential storm damage and outage estimates. Better outage estimates effectively enhance every other aspect of the emergency response process. Examples of these improved processes and insights include; enhanced outage management and preparation, reduced power restoration time, better information for the public, reduced unneeded asset deployment, forewarned emergency-response planners, better prepared staff, and resources efficiently dispatched to where they will be needed most. A mesonet purposefully designed using the QuantumWeather® Mesonet Design Tool Chain along with the Saint Louis University specifically tailored mesoscale model has been demonstrated to yield much better customer-focused weather forecasts and damage predictions than currently available through commodity information.

The result of this demonstration and analysis is an initial step in EPRI's endeavor to understand the value of supplemental sensing devices, which may inform more resolute storm incident awareness. The results shown are not recommended practice for positioning a network of sensors, but do represent one particular siting algorithm approach. Additional research (either planned or in progress) within the EPRI distribution modernization demo initiative is designed to evaluate how other types of sensors (mainly associated with internet of things) can supply enhanced storm situational awareness. Temporally the focus of other weather and condition sensing is focused on insights either prior to the event entering a service territory or during and immediately after the storm has passed. The emergent research is expected to have a significant impact on storm and outage forecasting within the next decade.

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