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Statewide Implementation of Salt Stockpile Inventory Using LiDAR Measurements: Case Study

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Abstract: The state of Indiana maintains approximately 120 salt storage facilities strategically distributed across the state for winter operations. In April 2023, those facilities contained approximately 217,000 tons of salt with an estimated value of USD 21 million. Accurate inventories at each facility during the winter season are important for scheduling re-supply so the facilities do not run out of salt. Inventories are also important at the end of the season for restocking to provide balanced inventories. This paper describes the implementation of a portable pole-mounted LiDAR system to measure salt stockpile inventory at 120 salt storage facilities in Indiana. Using two INDOT staff members, the end-of-season inventory took 9 working days, with volumetric inventories provided within 24 h of data collection. To provide an independent evaluation of the methodologies, the Hovermap ST backpack was used at selected facilities to provide control volumes. This system has a range of 100 m and an accuracy of ±3 cm, which reduces the occlusion to less than 8%. The pre-season facility capacity ranged from 0% to 100%, with an average of 66% full across all facilities. The post-season facility percentage ranged from 3% to 100%, with an average of 70% full. In addition, permanent roof-mounted LiDAR systems were deployed at two facilities to evaluate the effectiveness of monitoring salt stockpile inventories during winter operation activities. Plans are now underway to install fixed LiDAR systems at 15 additional facilities for the 2023–2024 winter season.

Keywords: LiDAR; salt; stockpile management; winter weather; winter operations

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1. Introduction

Stockpile inventory is a necessity for many industries to ensure that accurate quantities are reported to support daily operations and plan for restocking. Construction, mining, fertilizer, farming, and road deicing salt are just a few of the industries that need accurate estimates of stockpile inventories [1–5]. Current practices span visual estimation, unmanned aerial vehicles (UAVs), photogrammetry, and light detection and ranging (LiDAR) technology [1–4,6]. Traditional methods of surveying piles can expose crew members to dangerous situations, and visual estimation/truckload counts lead to the introduction of small systematic errors that accumulate over time [7,8]. Many new technologies require extensive mission planning, operator skills, software licensing, and data processing for a single location [3,8–11]. Depending on the size of the agency, operations and stockpile management expand over many unique and geographically distributed facilities. For the purposes of this study, the term stockpile refers to a pile of bulk material (salt and sand) used by transportation agencies. There are usually many stockpiles at one location, but a facility refers to a building used to cover and contain a specific stockpile. Typically, a facility only has one stockpile consisting of salt/anti-icing chemicals because the Environmental Protection Agency requires that salt is covered to prevent discharge in stormwater [12,13].

For example, the Indiana Department of Transportation (INDOT) manages over 120 salt storage facilities. The type of storage facility vastly varies by unit, as can be seen in Figure 1. Each type of facility offers its own advantages and disadvantages for storage, but this makes it challenging to acquire an accurate stockpile inventory. Expanding this across 120 sites (Figure 2), accurate traditional measuring becomes very challenging, and visual inspection estimates can vary greatly from location to location. INDOT is just one of many agencies with this issue. For example, the Maryland Department of Transportation (MDOT) manages 28 maintenance facilities, and the Wisconsin Department of Transportation (WisDOT) manages 287 state salt sheds [4,14,15].

(**A**) 71st Street Unit (**B**) Carbondale Unit

(**C**) Jasper Unit (**D**) Fort Wayne District Barn

(**E**) Wannatah Unit (**F**) Paoli Unit

Figure 1. Examples of distinct INDOT salt storage facilities.

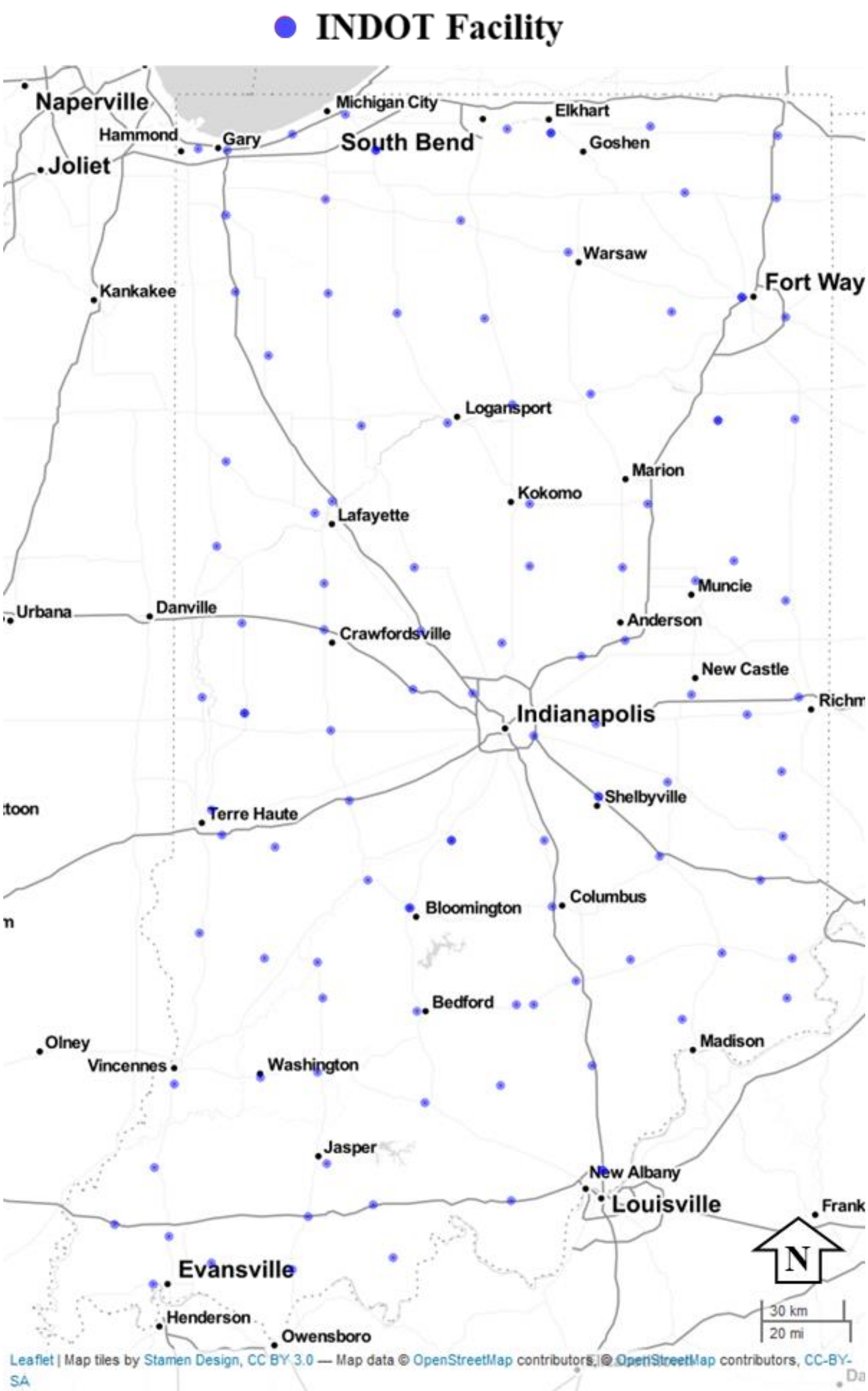


Figure 2. INDOT salt storage facilities and maintenance units.

2. Background and Literature Review

The timely application of deicing chemicals is vital to keep highways free of snow and ice. Daily inventory updates can aid in stockpile management, especially for roadway salt, to ensure there is enough material to properly treat roadways during a winter storm event [16–18]. Other industries have experimented with stockpile monitoring estimation and UAVs, but the covered nature of the salt piles limits their use, as the degraded global navigation satellite system (GNSS) signals affect the reliability and accuracy [19].

Photogrammetric techniques have been explored but require well-lit environments and overlapping images with distinct features [20]. Piled salt has limited distinguishable features, and many of the storage facilities are equipped with minimal interior lighting [21]. LiDAR provides a solution that overcomes the drawbacks of other systems. LiDAR does not require exterior lighting, making it a more suitable alternative compared to photogrammetry, and utilizing post-processing technique LiDAR via the SMART system can be registered and used even with a lack of GNSS signals available in the facility, which hinders UAV systems [22].

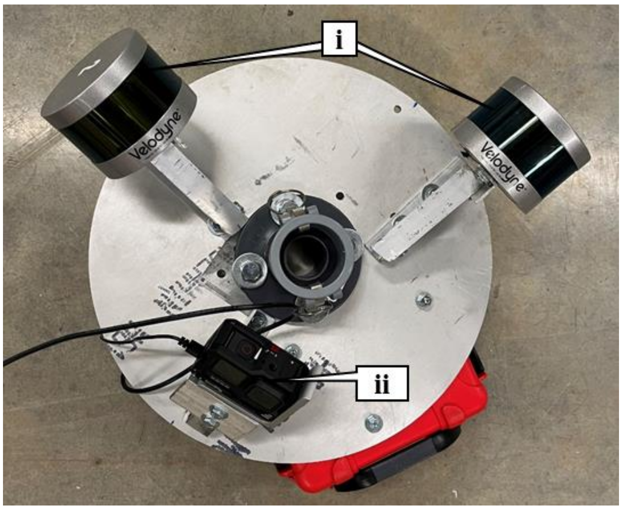
Agencies track salt stockpile inventory to manage the supply chain, monitor rock salt runoff into local environments, and, more recently, prepare for environmental reporting [23]. Integrating stockpile inventories along with other snowplow telematics provides a comprehensive view of salt distribution into the ecosystem to help mitigate the impacts and prevent overapplication [24,25]. Overapplication can leave salt residue on roadways, which can make it difficult for human and autonomous drivers to delineate pavement markings and the driving surface [26].

3. Objective and Scope

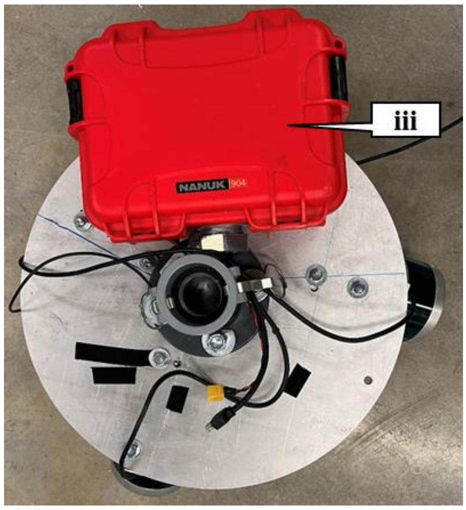
This study proposes and evaluates scalable systems to capture the volumes of stockpiles statewide. The developed systems expand on previous research through statewide utilization to provide insights into salt utilization and stockpile storage capacities. The study deploys a LiDAR-based stockpile management and reporting technology (SMART) system to expand on use cases based on the findings from portable and permanent deployments. This study collected data at 120 INDOT-managed salt facilities (Figure 2) and had a total of 280 scans to assess statewide inventory, monitor salt usage during a winter storm, and aid in restocking measures for the next season. The findings from this study can be expanded to other stockpiles, including but not limited to sand, aggregate, roadway patching material, crushed stone, and much more, which impact the architecture, engineering, and construction (AEC) sectors since an inventory of groundwork and supplies is crucial for building/maintenance projects.

4. Data Collection Equipment

The SMART system components used in this study are shown in Figure 3. Figure 3A shows the sensors mounted on the unit. There are two Velodyne VLP-16 Puck LiDAR sensors (callout i) and a GoPro Hero 9 RGB camera (callout ii). The Velodyne VLP-16 Puck 3D LiDAR is a spinning LiDAR that has an accuracy of $\pm$3 cm with a maximum measurement range of 100 m [27,28]. The sensor generates up to 300,000 points per second in single return mode, has a 360° horizontal field of view (FOV), and a 30° vertical FOV. The sensor weight is 830 g, consists of 16 laser rangefinders, has a horizontal angular resolution of 0.1–0.4°, and a vertical angular resolution of 2°. The angular resolution of the LiDAR unit enables an average point spacing within one scan line of 3 cm and between neighboring scan lines of 30 cm at a 5 m range (average distance to the salt surface) [21]. Although the salt pile could be scanned with one sensor, an additional sensor increases the area covered by the system. It also allows for more precise registration of successive scans. The GoPro Hero 9 RGB camera weighs 158 g, has a 23 Megapixel CMOS sensor, a horizontal FOV of 118°, and 69° vertical FOV. This enables the camera to cover roughly 460 square meters at a 10 m range [21,29]. Figure 3B shows the top side of the unit where the integration case is mounted. The integration case (callout iii) houses the wiring harness, Raspberry Pi (processing computer), and networking switch. This whole unit is then mounted on a telescoping pole attached to a hitch extender, which raises the device by approximately 6 m (20 feet) to acquire a good vantage point to collect data above the salt surface (Figure 3C, callout iv). The system is controlled through tablets and a push button to initialize the scanning.



(**A**) SMART System Sensors



(**B**) SMART System Component Case

(**C**) SMART Portable Hitch Mount

Figure 3. SMART System used for data collection.

5. Overview of Methodology

The SMART system's development, data acquisition procedure, and data processing strategy in this study are based on an early prototype system proposed by Manish et al., 2022 and Mahlberg et al., 2022 [4,21]. The orientation of the LiDAR units and camera field of view requires the 30-degree rotation to be performed seven times, with the LiDAR capturing 10-s-long scans at each increment. This results in LiDAR/RGB data collected over 180 degrees of rotation, the first scan being at 0 degrees and the final scan 180 degrees from the first. The proposed system from Figure 3A, equipped with two LiDAR units, collectively obtains a complete 360-degree scan of the facility, and the camera captures footage focused on the salt pile. Depending on the size of the stockpile, not all areas of the pile may be visible to the system at a given location, which would motivate the use of multiple scan stations for data collection.

After the data collection, the team uses the techniques from Manish et al., 2022 and Liu et al., 2023 to perform coarse and fine registrations of point clouds, which are then used to determine the stockpile volume [21,30]. First, an image-assisted coarse registration of the LiDAR scans is conducted wherein successive images are utilized to obtain scan-to-scan transformation through constrained iterative matching of the scale invariant feature transform (SIFT) features in two successive images at a time. Once the LiDAR scans are coarsely registered, a final optimization routine based on least squares adjustment is initiated for a feature-based fine registration of all scans [31]. Finally, to compute the stockpile volume, the fine registered point clouds are leveled with the ground surface, and the boundary of the salt pile is defined. Lastly, a digital surface model (DSM) is generated at defined grid cells (0.1 m by 0.1 m), with the center height for each cell established. The cells are then summed together to capture the total volume of the facility.

To check the accuracy of the SMART system, the Hovermap ST backpack was used at select facilities to provide independent control volumes. The Hovermap ST spinning LiDAR sensor has 16 laser rangefinders with a range of 100 m and an accuracy of $\pm$3 cm [32]. The horizontal FOV is 360° and the vertical FOV is 290°. This system is a mobile unit that utilizes LiDAR and inertial measurement unit (IMU)-based simultaneous localization and mapping (SLAM) to register point clouds in a unified coordinate system. This system can capture and provide accurate point clouds of the entire salt pile, reducing the amount of occlusion to less than 8%.

6. Statewide Inventory of 120 Facilities Using Portable Platform

As the agency prepares for the winter season, it is important to have an accurate pre-season inventory of salt. This ensures sufficient material when the winter season arrives. Two INDOT staff were trained to operate the system. The trained individuals each took a system and traveled across the state to capture 120 salt facilities with the portable SMART System and a hitch mount. The Purdue team processed the captured data and provided a digital surface model (DSM), a volume estimate value, and representative images from the data collection for verification. These outputs were crucial in ground-truthing the results and establishing confidence in the provided results to the agency. The reported results were compared to the agency's hand calculations, delivery tickets, and phone apps used by various units. If discrepancies between the SMART LiDAR volume estimates and the agency values were found, the Hovermap ST system was deployed to determine the volume of material at that facility. Once the discrepancies were resolved, the results were used as the baseline inventory for the facilities at the beginning of the season. A summary of the data was organized at the district, subdistrict, county, and unit levels to provide logistical and agency management with an idea as to how much salt they had in stock. This data collection was then repeated in March at every facility in 9 days to help determine what facilities could store additional salt for the post-season refill. These inventories were used as the baseline for the 2023–2024 statewide salt inventory going into the winter season. Figure 4 shows the pre-season and post-season salt total amounts in blue and red, respectively, by each district and capacity of the respective district. It is easy to note that the districts at the northern end of Indiana, LaPorte, and Fort Wayne have the highest capacity as they typically observe higher snow accumulations.

The high-level perspective is effective in helping determine what districts best utilize their storage facilities, but a more granular level with fewer units reporting to each district will help identify more exact shipping locations or routes of delivery trucks. Figure 5 below shows a similar graphic as Figure 4 but at the subdistrict level. This perspective gives an agency a better idea of where the specific allocation of salt may be. In the Cloverdale or Madison subdistricts, the facilities are almost at capacity in the pre-season and post-season, meaning none of the facilities in that subdistrict will require any salt. Alternatively, the Elkhart or LaPorte subdistrict facilities are only about half full compared to their capacity, meaning salt shipments could be delivered there.

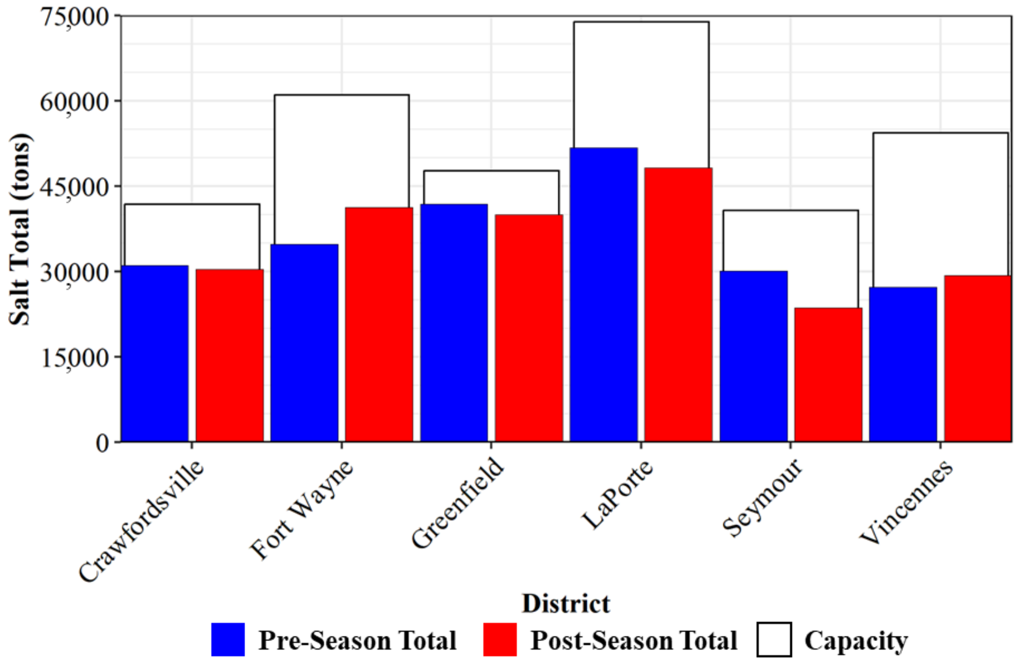


Figure 4. Statewide storage capacity and amount of salt stored by district.

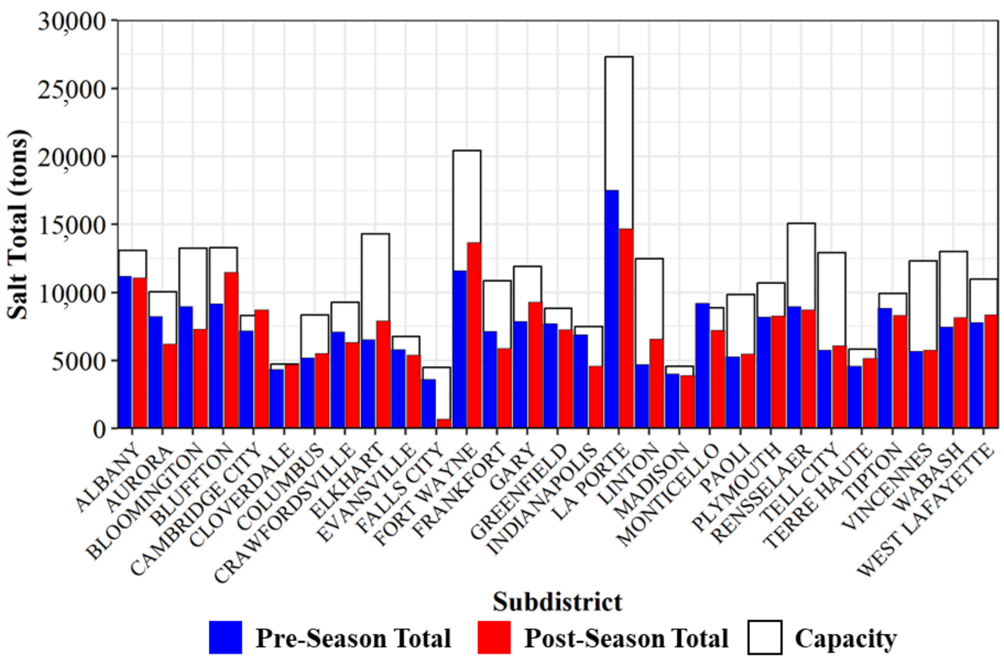
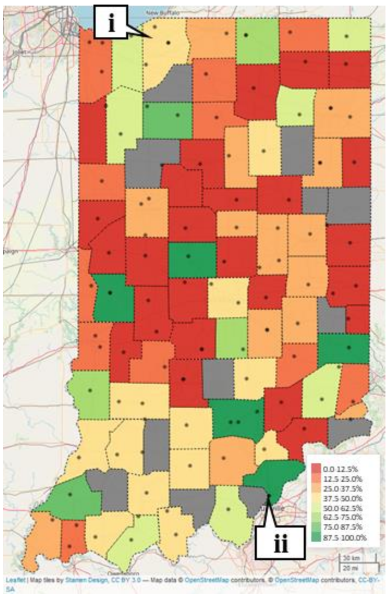


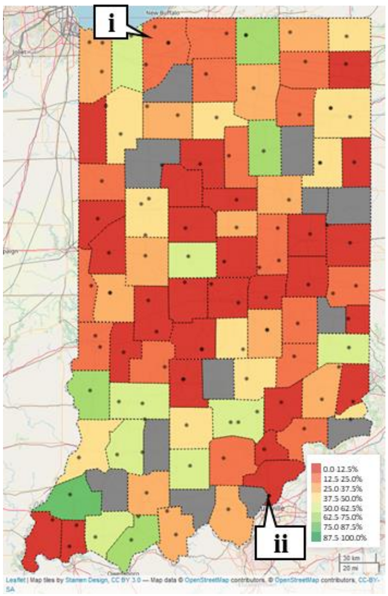
Figure 5. Statewide storage capacity and amount of salt stored by subdistrict.

7. Geographic Mapping of County Salt Inventories

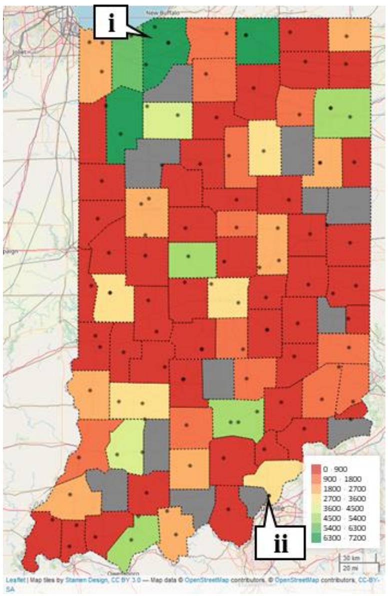
Figure 6 below shows the county each unit resides in, and the corresponding color represents how much available capacity there is. Figure 6A,B show the percent of available capacity in each county, with green meaning there is a large percentage of available storage and red meaning the facilities are near full. Figure 6C,D show a similar graphic but by tonnage available and not percent. Callout i in Figure 6 shows LaPorte county where it is apparent that between the pre- and post-season collection, the units received salt and were nearing capacity limits. The pre- and post-season percent available for salt was 41% and 21%, respectively. In terms of tonnage, the county had space for 6600 tons of salt before the winter season, and at the end of the winter season, through early refill operations, salt deliveries to the facilities only had room for 3400 tons. Callout ii shows Clark County, and Figure 6A,B show that the facility went from having 100% availability in their storage facilities to only having 10% availability. Observing that same county, Figure 6C,D show that salt was delivered, but the storage facility is not as large as the other facilities, taking the unit from having availability for 2900 tons of salt to room for only 300 tons of salt.



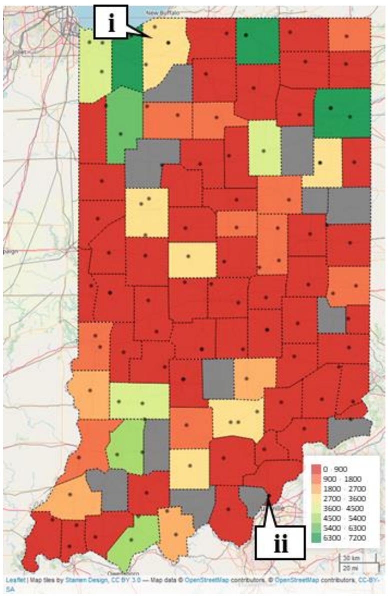
(**A**) Percent of Available Capacity
Pre-Season



(**B**) Percent of Available Capacity
Post-Season



(**C**) Tons of Available Capacity
Pre-Season



(**D**) Tons of Available Capacity
Post-Season

Figure 6. Available salt storage capacity by percentage and tons in each county.

The visuals developed in Figure 6 provide a context for salt delivery and scheduling at a county level. Among the counties, there is still an allocation of salt required to occur at each INDOT maintenance unit. Figure 7 shows the salt totals at each unit and their respective capacities. These values are important to the agency as each unit follows provided recommendations for material application and storage, but the units can also operate independently to meet the required level of service during a storm response. It can be noted that some facilities do not have pre or post-amounts, which is due to technical issues with the data collection. The data accuracy is limited by the pile structure and the amount of occlusion in the registered point cloud. The methods used to pile the salt vary by facility and the equipment available on-site, which results in unique piles and can create larger occlusion areas depending on the technique used. The methods used to process both barns and domes were developed to handle large areas of occlusion, but there were some facilities, mostly domes, that were too full, inhibiting the data collection equipment from entering the facility. Without the equipment being able to enter the facility, the occlusion of the pile exceeded 80%, and due to salt storage patterns, this led to higher inaccuracies. In Figure 7, some facilities do not have values for the pre- or post-season data, which is likely attributed to them being too full and having high occlusion rates.

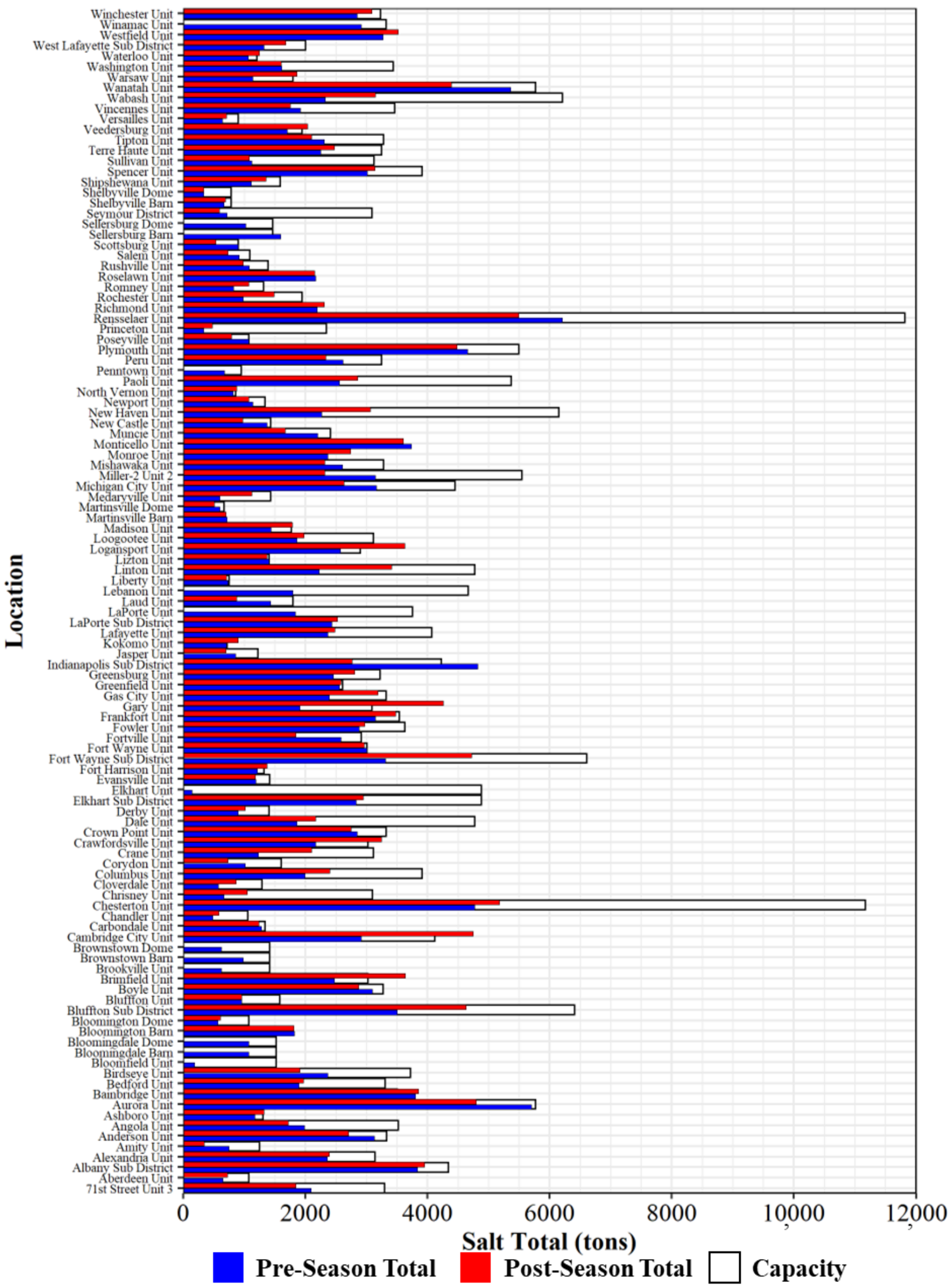
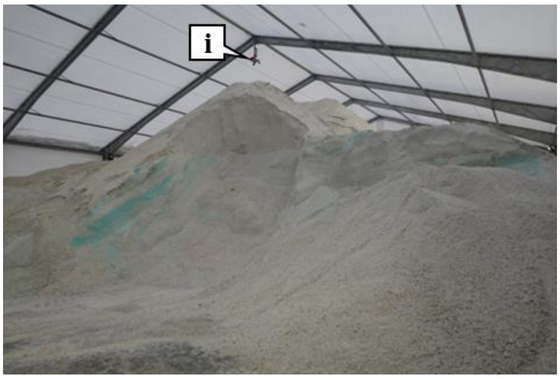


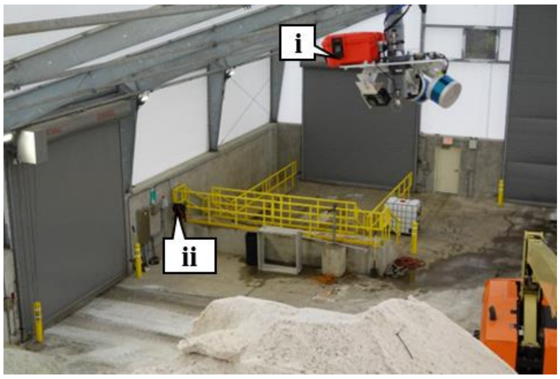
Figure 7. Statewide storage capacity and amount of salt stored by unit.

8. Fixed Salt Inventory Sensor Installations

The portable unit was effective at rapidly scaling statewide but only enabled scans to be performed twice in the winter season. A more scalable approach for this technology is desired and prototyped through a rugged permanent mounted system at the peak of the salt facility. Over the 2022–2023 winter season, two SMART systems were installed at the Lebanon unit and the Indianapolis subdistrict unit. The permanent installation at Lebanon can be seen in Figure 8. Figure 8A shows the position of the SMART system (callout i) above the salt pile situated at the peak of the facility. Figure 8B shows the SMART unit (callout i) and the user control box mounted at ground level for operation (callout ii). The permanent system reduced the data collection time to only two minutes. The data collection and processing were automated to the point where a user would only have to begin the scan by pressing a button on the controller and rotate the motor 30 degrees by pressing the preset buttons on the device. The files and photos were then automatically synced to the cloud for post-processing.



(**A**) SMART Permanent Install



(**B**) SMART Unit and Operating System

Figure 8. Permanent installation of SMART system.

The two permanent installations provide great value for stakeholders, as the systems enable agencies to see inventories in near-real time of their usage during a winter storm event and provide context on when to refill their facility. Figure 9 below shows the seasonal salt quantities at the Lebanon facility and the activity occurring at each. The ability to monitor the salt inventory over the winter season provided insight into salt usage and refill. Callout i shows the January winter storm that impacted Indiana and the salt used for that storm. Callout ii shows the refill measures the state performed to prepare for the next winter season.

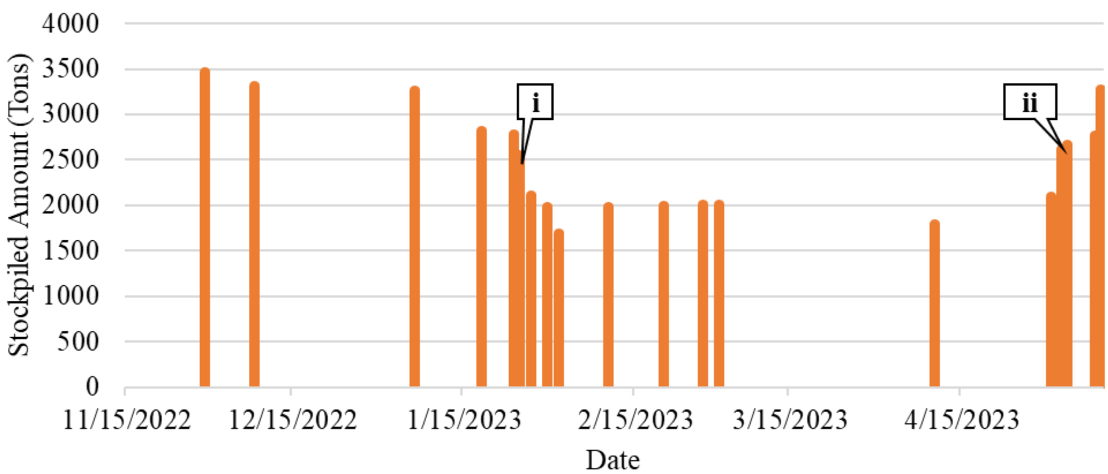


Figure 9. Winter 2022–2023 Lebanon salt stockpile inventory.

8.1. Winter Storm Usage Case Study

Permanent installations provide great seasonal awareness of salt usage and versatility. The advantage of the permanent installation is the ability to capture data without obstructing normal operations. An example of this can be observed for the 24–26 January 2023 winter storm (Figure 9, callout i). A scan was collected before the storm arrived on 24 January 2023. During the storm, a scan was taken as frequently as possible in between snowplow refills. Often, a scan was captured in between every truck, with a few instances where multiple trucks were refilled at the same time. The last scan was captured on the day of 27 January after a final clean-up on INDOT-managed roadways was complete. Figure 10 depicts each scan and the total amount in the salt facility. Throughout the winter storm, a total of over 500 tons was used to treat INDOT-managed roadways. A digital surface model (DSM) of the salt pile can be seen to be decreasing in size in Figure 11. Callouts i–vi in Figure 10 represent the DSM and GoPro images in Figures 11A–F and 12A–F, respectively. A summary showing every scan collected during the snow event can be found at doi:10.4231/4MAG-JN90.

The digital surface model curated in Cloud Compare shows the salt piles colored by height in Figure 11 [33]. Red indicates a height of 5.48 m (6.0 yards), and blue indicates the ground surface or 0 m (0 yards). These DSMs provide context for the salt usage during the storm. Figure 11A is the first scan taken before the storm. Figure 11B is a scan taken mid-storm after approximately 290 tons were used. It can be noted between Figure 11A,B that salt is removed at callout i and ii. Between Figure 11B,C, 53 tons were used as denoted by callout iii. Approximately 30 tons were used between Figure 11C,D, as denoted by callout iv. Figure 11E,F show a difference of 164 tons, with the salt usage being depicted by the respective callouts v, and vi.

The same scans from the DSM in Figure 11 can be observed in the representative GoPro image in Figure 12. These images help validate what is observed in the DSM and show how the salt is being used. The images also show the salt with additives on the right with a green hue and untreated salt on the left appearing white.

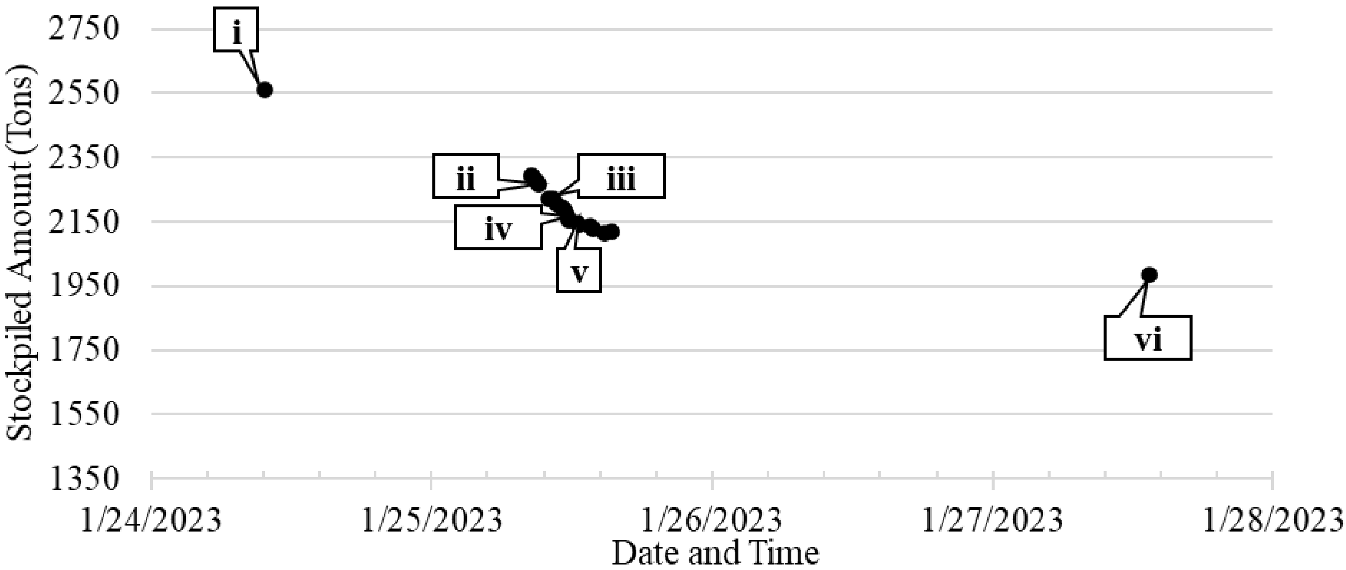
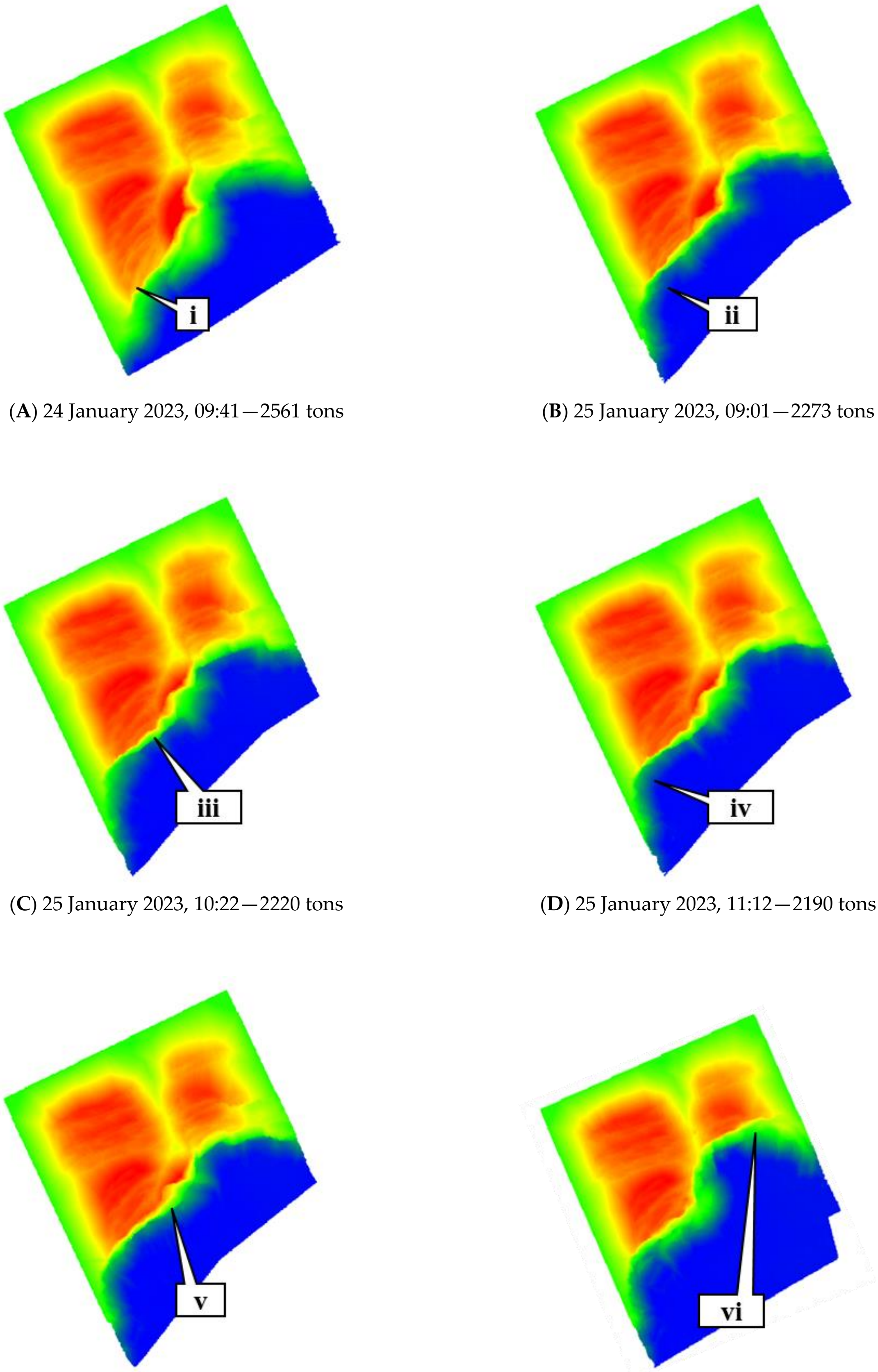
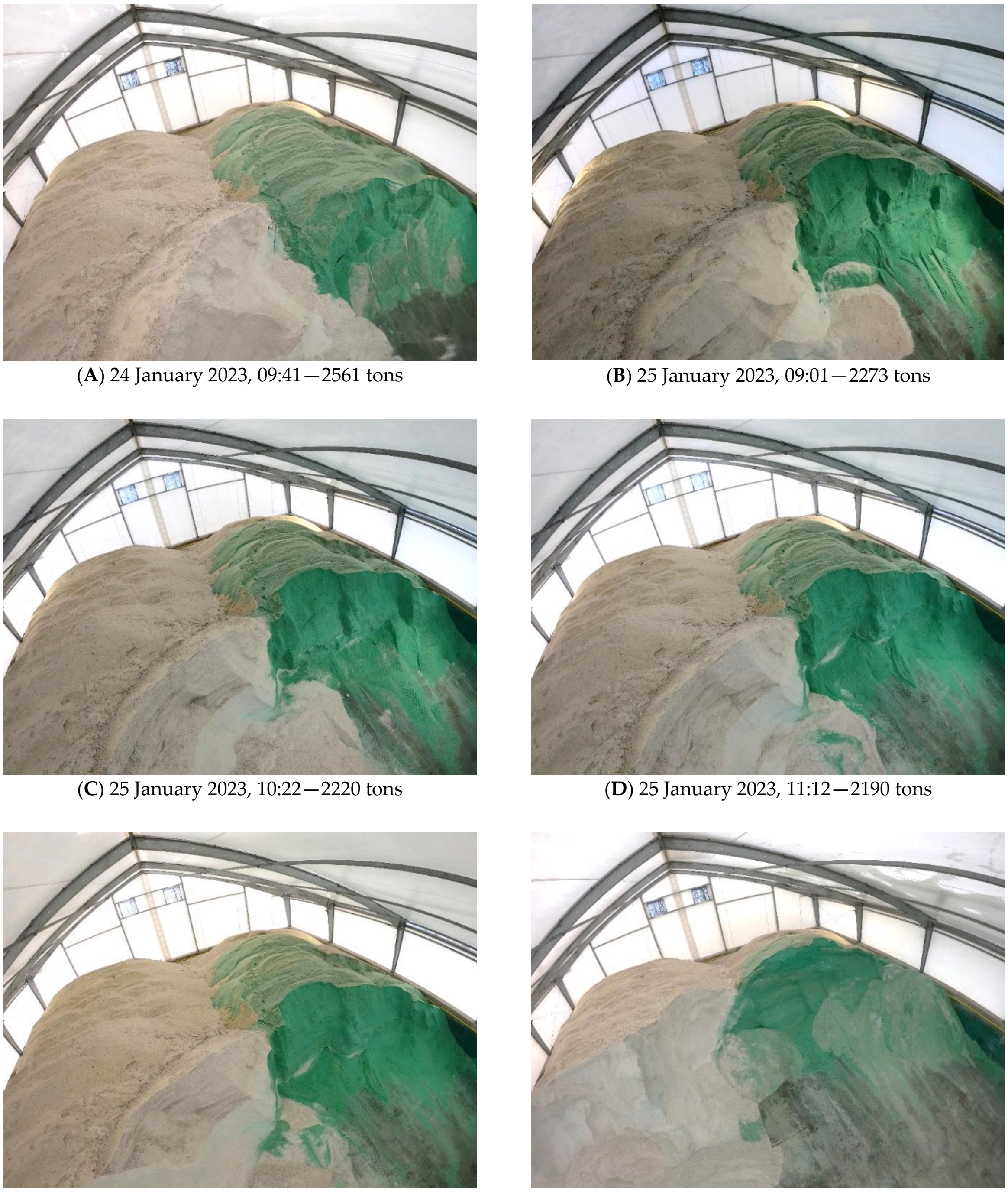


Figure 10. 24–26 January 2023 winter storm salt usage.



(**A**) 24 January 2023, 09:41—2561 tons
(**B**) 25 January 2023, 09:01—2273 tons
(**C**) 25 January 2023, 10:22—2220 tons
(**D**) 25 January 2023, 11:12—2190 tons
(**E**) 25 January 2023, 12:30—2148 tons
(**F**) 27 January 2023, 13:00—1984 tons

Figure 11. Digital surface models of Lebanon salt over January 2023 winter storm.



(**A**) 24 January 2023, 09:41—2561 tons
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(**D**) 25 January 2023, 11:12—2190 tons
(**E**) 25 January 2023, 12:30—2148 tons
(**F**) 27 January 2023, 13:00—1984 tons

Figure 12. GoPro images of Lebanon salt over January 2023 winter storm.

8.2. End of Sesaon Salt Replenishment Case Study

Similar to salt usage during a winter storm, it is valuable to monitor salt refilling activities to prevent an excess of deliveries to a facility that would exceed capacity. Figure 13 below shows the Lebanon unit, as the facility received truck shipments for their post-winter restock of approximately 1800 tons of salt. Callouts i–vi from Figure 13 are representative examples that can be shown as a DSM in Figure 14 and a photo from the GoPro in Figure 15. The callout i corresponds to "a" in both Figures 14 and 15, and callout iv corresponds to "f" in both figures, respectively. A timelapse of the refill operation and a summary of all the scans collected during the May refill can be found at doi:10.4231/CBH3-3019.

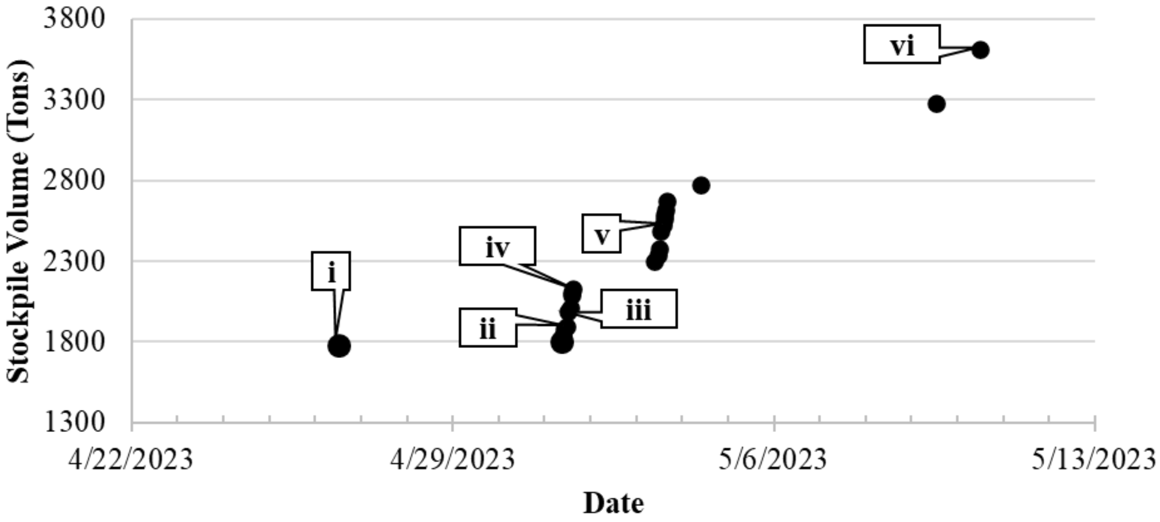
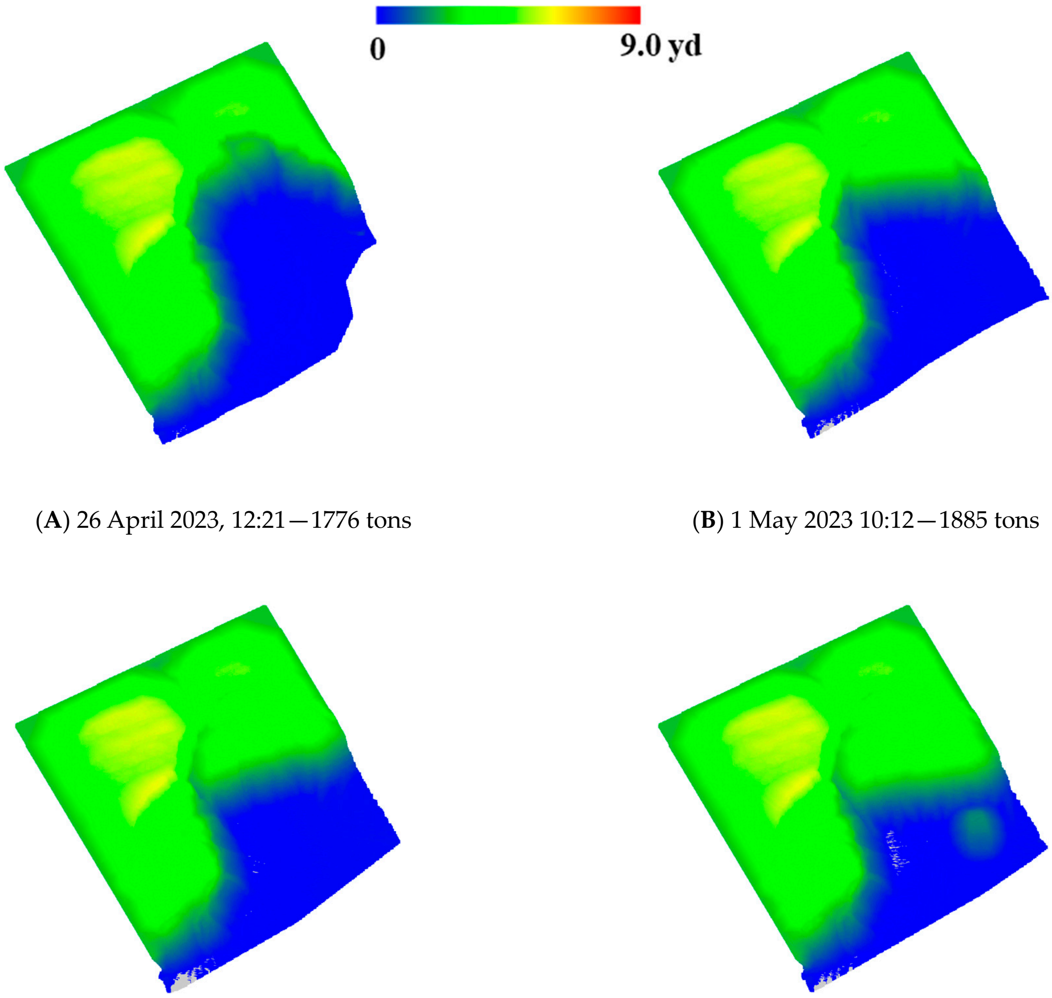


Figure 13. 26 April–10 May 2023 salt refill.



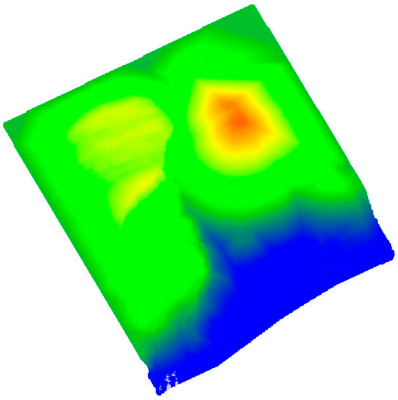
(**A**) 26 April 2023, 12:21—1776 tons

(**B**) 1 May 2023 10:12—1885 tons

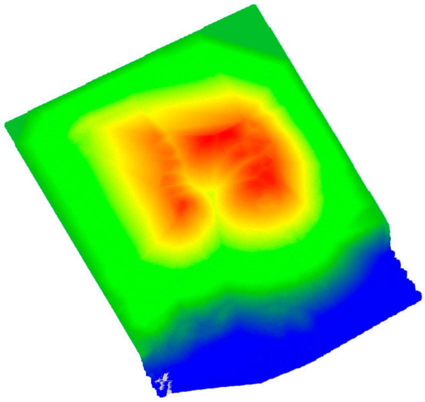
(**C**) 1 May 2023 13:28—2014 tons

(**D**) 1 May 2023 14:33—2128 tons

Figure 14. *Cont.*



(**E**) 3 May 2023 12:58—2489 tons



(**F**) 10 May 2023, 12:06—3615 tons

Figure 14. Digital surface models of Lebanon salt over Spring 2023 refill.

Figure 14 shows the DSM of the salt pile as the unit is refilled. The DSM is colored by height and models the salt accurately. The DSM progressively filled in with green in Figure 14A through Figure 14D when the salt was being loaded with a payloader. On 3 May 2023, the Lebanon facility used a conveyor to convey their remaining salt deliveries, which can be noticed by the peaks (red) on the DSM.

(**A**) 26 April 2023, 12:21—11,776 tons

(**B**) 1 May 2023 10:12—11,885 tons

(**C**) 1 May 2023 13:28—2014 tons

(**D**) 1 May 2023 14:33—2128 tons

Figure 15. *Cont*.

(**E**) 3 May 2023 12:58—2489 tons (**F**) 10 May 2023, 12:06—3615 tons

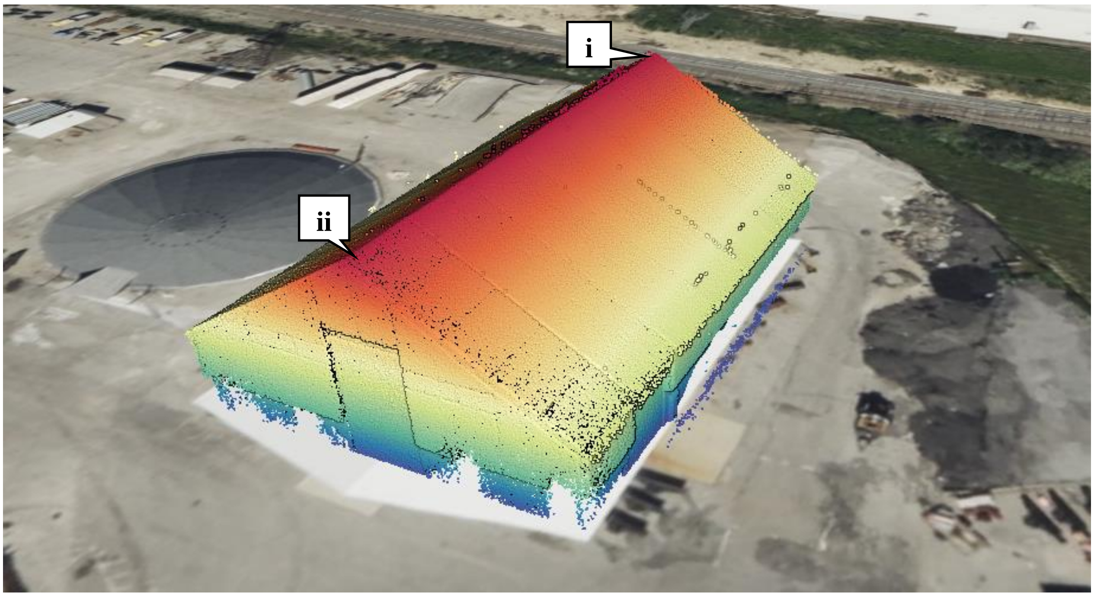
Figure 15. GoPro images of Lebanon salt over May 2023 salt refill.

The representative GoPro images for refills can be found in Figure 15. These images provide context and ground truthing for the DSMs in Figure 14. The conveyor that was used to bring the facility closer to capacity can be seen in Figure 15E,F.

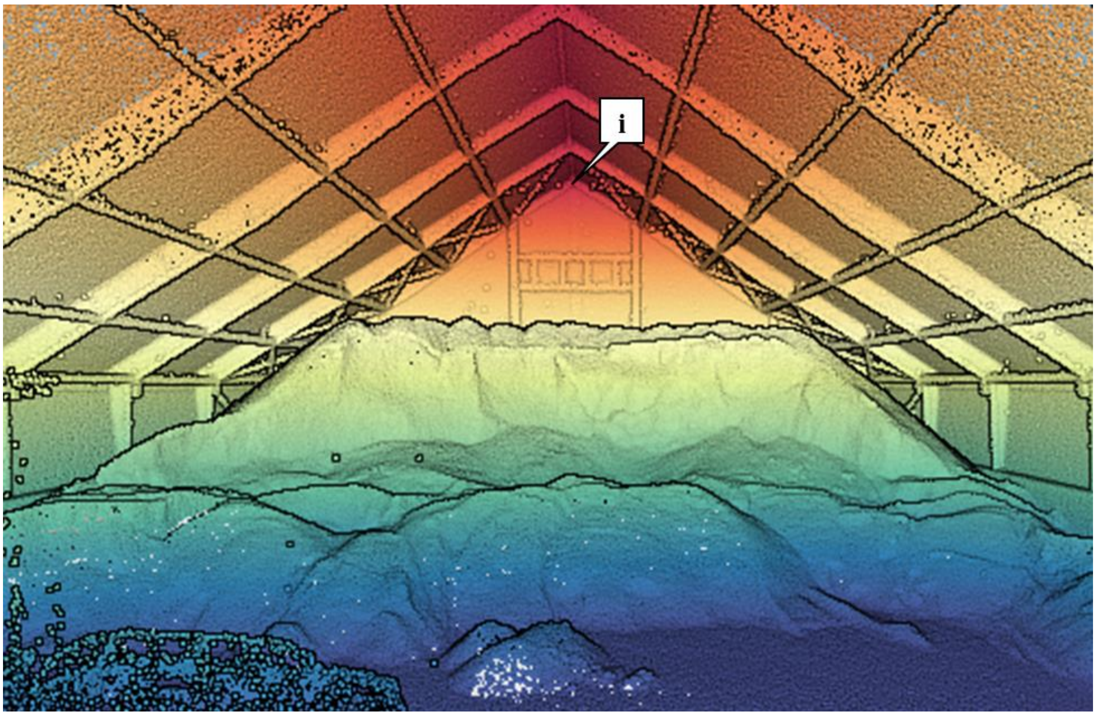
9. Evaluating Statewide Scalability

Previous studies evaluated the accuracy of the SMART system by repositioning salt from one location in the salt facility to another. Scans using the SMART system and terrestrial laser scanners (TLS) were captured before and after moving the salt. The results found that the system had a volumetric error of less than 1% [4,21]. For this study, similar comparisons were made using the Hovermap ST system (33). Over the 2022–2023 winter season, there were over 280 scans collected statewide. Due to the cost, the time required to capture the data, and safety concerns, the Hovermap ST system was used only for validation at a few facilities where the stockpiles could be walked on safely. For 17 scans, the Hovermap ST system was used in conjunction with the SMART system to provide validation of the results. The Hovermap ST backpack system was mounted on the back of a team member to collect data on the entire salt. The advantage of the Hovermap ST system is the reduction of occlusions when moved across the pile, and it acts as the baseline for the volume estimates. Across all 17 scans, the average occlusion of the Hovermap data was 1.84%, with a maximum of 7.32%. The average occlusion for the SMART system was 58.12%, and the maximum was 75.30%. Between the two systems, the error of volume estimates among the 17 scans on average was 1.58%, with a total of over 55,000 tons evaluated.

The conclusions from the prototypes have resulted in an expanded effort for further fixed installations statewide. The agency considered the technical, operational, and financial aspects of implementing this technology statewide, and, based on feedback from this study, the agency wishes to further implement the technology. Recent developments in LiDAR sensors have greatly improved the sensors by eliminating moving parts, providing a larger field of view and more scan lines. Due to these new developments, the exact mounting locations will vary and will be determined by the building size and height. Pending size, height, and mounting attributes, multiple sensor locations may be required. The testing performed using the installed prototypes indicates that the new sensor location should be at the peak of the facilities (as high as possible) and located at the ends of each building peak. Figure 16A shows a point cloud from a LiDAR scan conducted in the INDOT salt barn at the Ft Wayne District. Callouts i and ii show the approximate locations anticipated for permanent implementation. Figure 16B shows the interior of the building and the salt pile. Callout i shows the same location as callout i in Figure 16A but shows the interior suggested mounting location at the peak of the building. Power and internet would be needed at the apex of the buildings in the front and back to support the sensors. Each of these locations would require a conduit to be run to a ground-level National Electrical Manufacturers Association (NEMA) enclosure or environmentally protected electrical box that can provide internet and power over ethernet to the sensors. The box should be easily accessible, and all the installed equipment will be required to be rated IP67 or better to protect against the corrosive salt environment. Final verification of the mounting locations and required equipment will be conducted through the end of 2023. Fifteen new permanent LiDAR systems are planned for deployment in advance of the 2023–2024 winter season. These deployments will aid in keeping an accurate inventory of the installed facilities. The portable systems will be used over the winter season to validate the permanent installations and intermediately to capture data as requested over the winter season.



(**A**) LiDAR Scan of Exterior of Salt Facility



(**B**) LiDAR Scan of Interior of Salt Facility

Figure 16. Approximate permanent LiDAR sensor mounting locations for the Fort Wayne salt barn.

10. Conclusions and Future Scope

This study showed the use and validation of the new stockpile monitoring and reporting technology (SMART) system that utilizes two LiDAR sensors and a camera to determine accurate volume estimations of salt stockpiles. A portable system was deployed twice at every INDOT-owned salt facility for pre-season inventory and to capture base-level inventories to allocate post-season refills. The pre-season inventories were found to be 213,000 tons, and the post-season inventories were found to be 217,000 tons. The pre-season facility capacity ranged from 0% to 100%, with an average of 66% full across all facilities. The post-season facility percentage ranged from 3% to 100%, with an average of 70% full. As experience with the portable system increased, two INDOT staff completed the post-season data collection at 120 facilities in 9 days and enabled the agency to purchase and allocate an additional 51,000 tons of salt statewide (approximately USD 5 million) (Figure 7).

The 2022–2023 winter season also had two permanently fixed assets in facilities, which monitored seasonal salt usage, salt usage of over 500 tons during a winter storm event, and a spring refill of over 1800 tons. The utilization of the developed technology has provided insight to INDOT into their salt usage during the winter season, identified facilities with high salt usage and/or low inventory, and provided quantitative data for allocating seasonal salt purchases. In total, 15 new permanent LiDAR systems are planned for deployment in advance of the 2023–2024 winter season, with an IPX6 rating on field-hardened capabilities. These systems have no moving parts and will be able to provide hourly and daily updates of stockpile inventories.

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