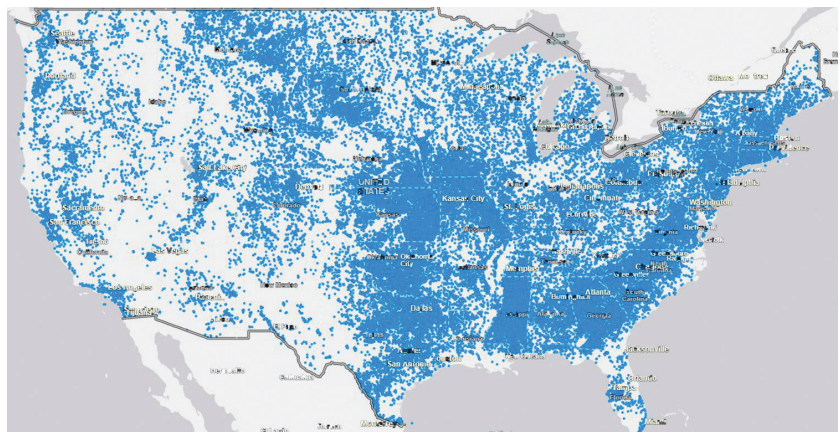


Soil Moisture Analysis

By Paul Gagliardo

THE WORLD'S DAMS AND LEVEES ARE ESSENTIAL INFRASTRUCTURE USED TO STORE WATER, control flooding, provide recreation and generate power. Dams and levee networks are designated as critical infrastructure and over their expected life exposed to multiple hazards, including flooding, storm surge, erosion, debris flows and damage to control equipment and gates. The exact number of dams and levees world-wide is unknown.

According to the AMBER Consortium's Barrier Atlas there are an estimated 1.2 million in-stream barriers spread across Europe's 36 countries and 147 rivers. Approximately 61,500 of those barriers are dams. The average age of the dams in the United Kingdom and Japan is over 100 years old. Germany, Italy and the United States have an average age between 60-70 years. Experts often use the 50-year mark as the "alert



U.S. Dam Locations from National Inventory of Dams 2024.

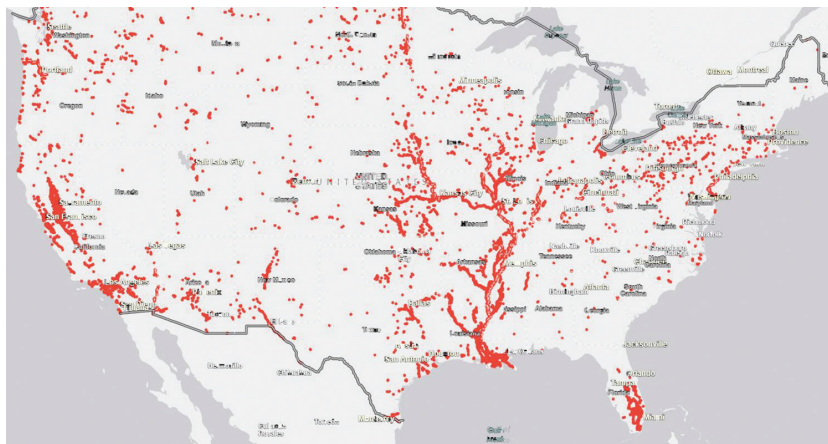
age" where additional monitoring and maintenance should be implemented to extend the life of the asset. In Europe there are no standardized flood protection levee datasets.

The United States has a National Inventory of Dams that contains a comprehensive list by state. In total, the United States has 92,092 dams that

average 61 years of age. Only 6% are regulated by the Federal Government and 70% are state regulated. About 64% of the dams in the United States are privately owned, 4% owned by the federal government, 20% local government owned, 7% state owned and another 4% owned by public utilities. About 80% of the dams in the



Using L-Band Radar to Manage Risks in Earthen Dams and Levees



U.S. Levee Locations from National Inventory of Levees 2024.

United States are earthen dams. 76% of the dams are considered high hazard potential dams.

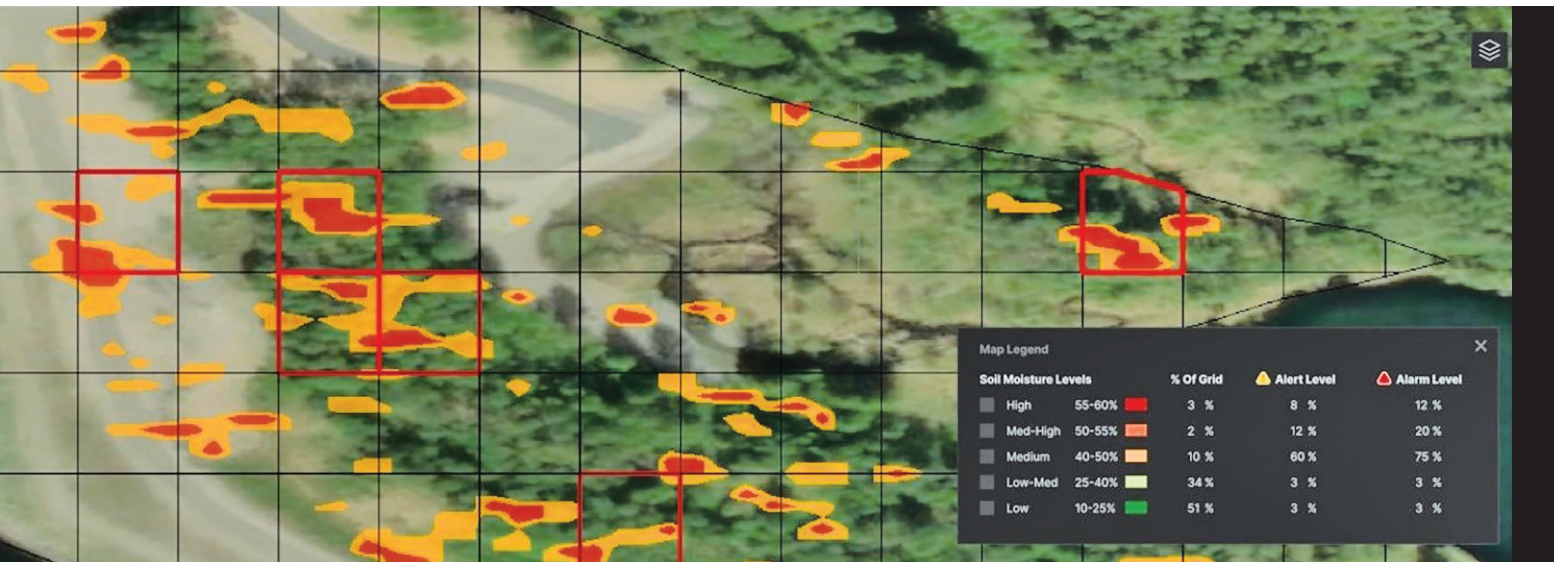
There are a total of 6,972 levee systems in the United States comprised of 24,513 miles of levees. Approximately 70% of the levees in the U.S. are locally owned by either levee districts/water management districts (56%), municipal

government (10%), or County/Tribal government (4%). The remaining roughly 30% are owned by the Federal government's U.S. Army Corps of Engineers (USACE).

The majority of levees are earthen embankments, some covered with grass, gravel, stone, asphalt, or concrete. Earthen levees can fail due

to many different causes including overtopping, seepage, settlement, cracks, animal burrows or vegetation growth on embankment. Climate change is expected to change the duration and intensity of storm events, further increasing the risk of failure. The average age of levees in the United States is 58 years and the most recent estimates to repair and rehabilitate them is approximately \$100 billion and growing over time.

The American Society of Civil Engineers' 2021 Infrastructure Report Card gave both dams and levees a D grade. Every state except Alabama has established a regulatory program for dam safety. Dam inspections are required every three to five years. These inspections are focused on observing the outlet conduits, spillways, dam faces and toes, and downstream channels. There is currently no national standard for levee design, construction, operation, or maintenance.



Algorithm output showing levels of soil moisture.

The majority of earthen dam and levee failures are caused by seepage that results in internal erosion and ultimately hydraulic or structural failure. Increased seepage increases the soil moisture content and impermeability of the structure can no longer be guaranteed. Internal erosion results in soil particles being carried downstream forming channels, increasing pore pressure, and initiating flow of interstitial water. These conditions all lead ultimately to failures.

Seepage can occur through piping along outlet walls, abutments, or foundations. It can occur directly through embankments or due to the deposition of water-soluble materials. Seepage can also occur due to vegetation growth or burrowing animals. Since seepage is a hidden condition and that physical inspections are relatively rare events, being spaced out over years, a new way to determine if ongoing issues are inherent in earthen dams and levees is required to manage risks.

A recent study measured soil moisture data using traditional methods, lab-testing field-collected soil samples for gravimetric water content (GWC) and used this data to calibrate data provided by ASTERRA EarthWorks, which uses propriety algorithms to interpret synthetic aperture radar (SAR) images taken by satellite. L-Band SAR instruments have the ability to detect underground soil moisture. The experiment

demonstrated that satellite soil moisture mapping can be effectively used to identify at-risk infrastructure by providing a useful and valuable new data set. This new data can locate areas of subsurface moisture that translates into drainage problems or geotechnical instabilities near critical infrastructure. Individual locations can then be prioritized for investigation, inspection, and mitigation. This information is also an early warning of potential threats as initial soil moisture buildup in dams and levees cannot be seen at the surface. It allows measures to be taken to alleviate issues and extend the life of these assets. The image below shows a map with five levels of soil moisture identified within the study area where the GWC data was correlated with the satellite imagery data.

This data layer can be used by private owners, government agencies or engineering companies to provide an early warning risk profile of earthen dams and levees. The information can detect changes in soil moisture content along an extensive series of assets over time to determine the progression of issues. It can direct operators to areas of potential failure so that physical inspections can be made to identify problems and make repairs. In addition, this information can be used to deploy other tools such as in-ground sensors to directly and immediately detect increasing soil moisture levels, or InSAR technology to

detect the onset of slope displacement or acceleration.

The U.S. Army Corps of Engineers (USACE) estimated that in 2019 their flood risk management projects prevented \$348 billion in damages. They calculated that flood damage reduction projects avoid \$12 of damages for each \$1 invested. This underscores the value proposition of active dam and levee management programs. In FY2020 USACE budgeted \$363 million for capital improvements to existing dams and \$50 million for routine dam safety programs. It is estimated that it will require \$20 billion in funding and 50 years to repair all dams in their portfolio. This level of funding is not available thus reinforcing the need to identify new techniques for leveraging the budgets allocated to increase the efficiency of management and inspection efforts and extend the life of assets.

The early identification of areas of earthen dams and levees with excessive soil moisture has a number of benefits. The ability of satellite imagery to triage the asset allows the owner to direct inspection resources to specific areas that require the most attention. This makes the physical inspection process more efficient and lowers the overall costs associated with this effort. Knowing the areas that are at the most risk informs the owner as to where it should deploy other inspection and data gathering devices and thus directs the operating

cost of inspection and monitoring and the capital costs of modifications and repairs more efficiently. When issues can be identified earlier, thus avoiding catastrophic events, the life of the assets can be extended. This allows for capital dollars to be allocated more appropriately focusing on the assets that are most at risk. The capital budgets for replacement can be extended over further years, allowing for more assets to be rehabilitated with the same funding.

In order to analyze the value proposition of a satellite inspection program related to operations costs it is necessary to understand the current tasks that must be implemented according to rules and regulations for dam safety. At minimum, a weekly physical inspection of the dam must be performed. The inspections include looking for seepage and wet areas near drains and conduits and at the toe of the dam, cracking of the dam face, rodent activity, trees and brush, dam crest settlement and internal erosion.

The Texas State Soil and Water Conservation Board (TSSWCB) estimates it costs an average of \$30,000 for dam operation and maintenance in 2023 for a 188-dam inventory. Another \$370,000 per dam for engineering services is also required for proper management of those assets. An

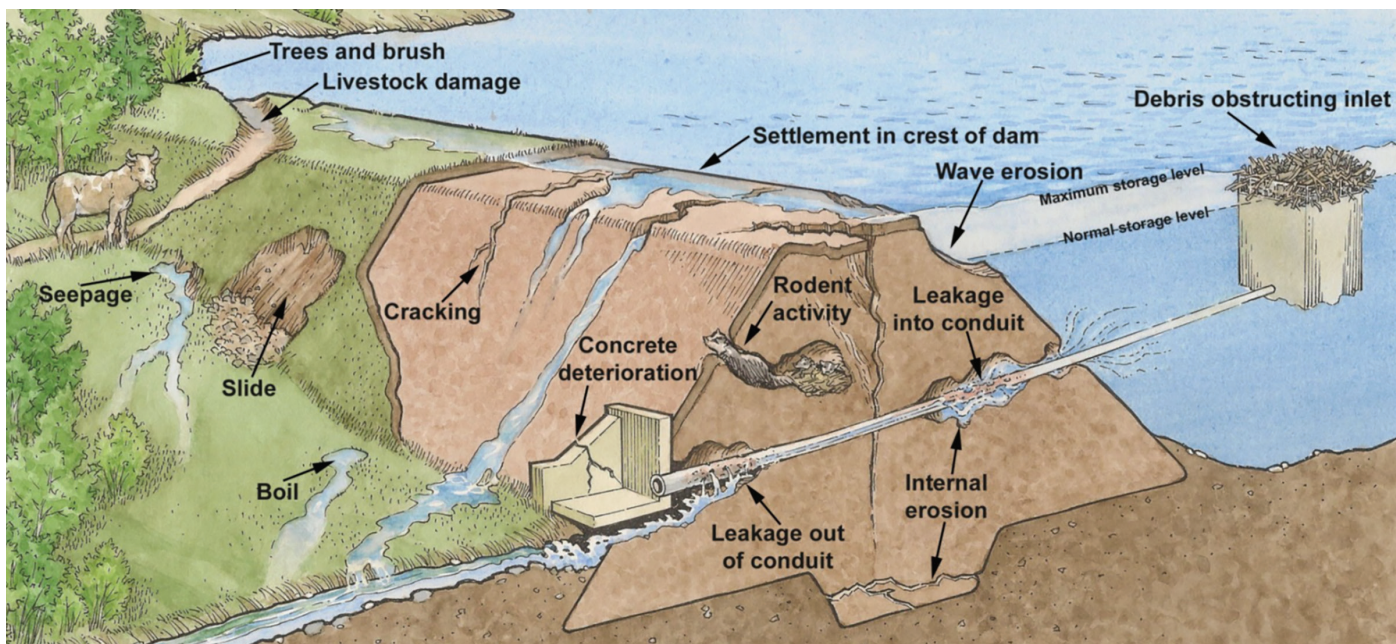
average of \$560,000 was budgeted for the repair of 15 dams in 2023. The average for three repair projects completed in 2022 was \$703,000. For a larger inventory of 2041 dams in Texas an average of \$102,000 per year is budgeted for maintenance, operations, and repair for each asset. One full scale rehabilitation project was completed in 2022 at a cost of \$4,200,000. Using satellite imagery inspection staff can be directed to the highest risk locations and reduce their effort by up to 50%. Additionally, the costs of repairs can be reduced by 25% because the problem areas are identified earlier when they can be fixed at lower cost. This also reduces the engineering services needed. The cost for full-scale rehabilitation can be reduced by a minimum of 10%.

Each dam operator/owner could realize a simple payback of significantly less than one year when utilizing satellite imagery as a tool for inspecting earthen dams.

The satellite survey costs can vary depending on the frequency of images collected during the study time period. The image covers an area of 1,200 square miles so a number of dams could be included in each survey thus reducing the overall cost of each project significantly. A budget estimate for an individual dam inspection is

\$40,000 per year. Based on a projected savings of \$51,000 a simple payback of 9 months is possible solely based on reduced operations and maintenance costs. Dam repair costs can exceed \$500,000 per asset. These costs can be reduced by at least 25% due to the early identification of issues. This reduces the cost of repair. Another savings of \$140,000 can be realized on an average repair. The design life of dams is 50 years. Many are already older than this. A full rehabilitation of a dam can cost \$4,200,000. The satellite inspection program can focus rehabilitation efforts and reduce the cost by at least 10%, saving a further \$420,000 over the life of the asset.

There are many routine maintenance activities related to levees. These include physical inspections, mowing and animal control. Non-routine maintenance program tasks include pipe and slope repair, channel clearing and drainage management. Most of these activities are performed by boots-on-the-ground personnel and require a physical inspection of miles of levees before repairs and maintenance can be planned and conducted. Using the satellite imagery inspection tool this physical inspection can be done more efficiently. The remote observation technology can inspect many miles of levees and provide a report



Common inspection and maintenance issues.

documenting the most at risk areas to be physically inspected.

Based on the USACE National Levee Program Cost Data 2023 report, a 10-mile, 15-ft-tall levee can experience a yearly maintenance cost of \$1,200,000. At least half of that cost is related to repair costs such as inspections, channel maintenance, erosion repairs, crown maintenance, and embankment repairs. Based on a 25% reduction in maintenance cost due to the improved data and knowledge provided by the satellite imagery a cost savings of \$300,000 is possible. Due to the linear nature of levees as compared to dams the satellite imagery cost is higher. Assuming a cost of \$150,000 per year to provide satellite-based analysis of the levee soil moisture levels, a six-month payback is achievable.

The satellite information provided can also prevent catastrophic levee failure by identifying sections that

EARTHEN DAM COST SAVINGS USING SATELLITE IMAGERY INSPECTION				
	Budgeted Cost	Improved Efficiency	Revised Cost	Savings
YEARLY O&M	\$102,000	50%	\$51,000	\$51,000
REPAIR	\$703,000	25%	\$528,000	\$175,000
LIFE EXTENSION	\$4,200,000	10%	\$3,780,000	\$420,000

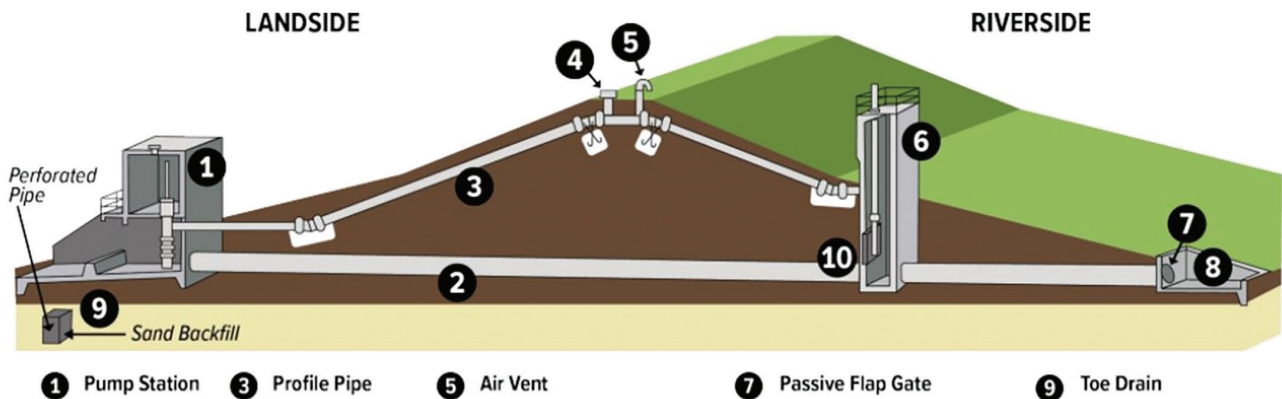
are at extremely high risk. This can be done even when the damages that cause failure are hidden. It is estimated that the cost to construct a typical 15-ft earthen levee is over \$500,000 per mile. This does not take into account the damages caused by a levee failure and the removal of the old debris. Preventing a total levee failure is an added value to the subsurface soil moisture analysis that L-Band satellite imagery can provide.

Satellite L-Band radar imagery can detect soil moisture levels in earthen dams and levees that cannot

be detected by visual inspection. This triage can reduce the physical inspection time and effort of owners and operators and direct limited resources to areas with the highest degree of risk. This lowers the overall maintenance cost and extends the life of the asset. It also reduces the ongoing repair, rehabilitation, and replacement costs.

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INTERIOR DRAINAGE SYSTEM



Typical Levee Cross-Section.

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