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Monitoring inrush risk with mXrap: from idea to reality

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Abstract

Inrush events pose a significant hazard in block and sublevel cave operations, with historical incidents resulting in fatalities and ongoing operational risks. Effective management of this hazard requires timely interpretation and communication of complex datasets, yet traditional approaches often rely on fragmented tools and manual processes that limit visibility and responsiveness.

This paper presents the development of a customised inrush management application within the mXrap (Harris & Wesseloo 2015) platform, designed to integrate multiple data sources and provide an intuitive, visual interface for risk assessment. Over a 24-month period, Resolve Mining Solutions collaborated with several established block cave operations to transform a conceptual idea into a functional and commercially available tool that supports both operational and management decision-making. Key features include the import and visualisation of drawpoint observations, rainfall tracking, and integration of GEOVIA PCBC (2026) data for fines prediction. The application calculates inherent and residual risk using site-specific trigger action response plans, displays results in 3D, and enables time-based filtering for trend analysis. Additional enhancements include heatmaps, observation-versus-prediction comparisons, and spill event visualisation to improve communication of risk across the workforce.

By leveraging existing mXrap functionality and applying targeted customisations, this project demonstrates that advanced hazard management tools can be developed without extensive programming expertise or high cost. The resulting platform reduces reliance on multiple applications, improves transparency, and provides a scalable framework for managing one of the most critical hazards in caving operations.

Keywords: *inrush, principal hazards, risk management, monitoring, mXrap*

1 Problem definition

Inrush, or mudrush, is universally recognised as a major hazard to cave operations (International Caving Research Network 2026) and in many jurisdictions is identified in legislation as a principal hazard requiring specific management plans within the mine safety framework. It is typically defined as a sudden and uncontrolled inflow of material (water, mud or fine-grained material) into a working area (Widijanto et al. 2012). This paper utilises the terms interchangeably; however, there is a range of terms and definitions that reflect its complex and variable nature as outlined by Musolino et al. (2024). The fines and moisture content are typically the environmental conditions that impact the potential for inrush, with the presence of a discharge point (i.e. the drawpoint) and a stimulus (e.g. bogging or seismic event) being the 2 remaining parameters outlined by Butcher et al. (2005) for an inrush/mudrush event to occur. As highlighted by Mussolino et al. (2024) however, there is a variability in inrush style, triggers, and definitions across the industry, requiring a somewhat customised solution to management strategy, including data analysis and interpretation. Due to its potential to cause multiple fatalities (Jakubec et al. 2012), inrush is also ranked in the upper corner of most risk matrices, especially where caving operations are located in environments with high water inflow.

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Inrush/mudrush events can occur in both sublevel and block cave mines, require fine material and can occur with and without the presence of water (Hubert et al. 2000) as seen in Figure 1. Where water isn't present, a dry inrush can occur, as has been observed at Cadia East (Osorio 2025) and Northparkes E48 (Snyman & Webster 2022). There are several events that can trigger inrush events, including seismicity and secondary blasting activities in the vicinity of the drawpoint, along with bogging activities. Anything that can introduce energy into the cave column above the drawpoint and dislodge material can potentially generate a flow path for fines to rapidly enter the mine, usually on the extraction level. Whilst there is seemingly an element of randomness in the occurrence of inrush events, there are contributing factors that can be monitored to highlight where an elevated risk of these events occurring exists. These factors are water inflow and fragmentation at the drawpoint scale. By monitoring trends and the co-occurrence of increased fines and water inflow, a forecast of inrush potential can be developed.

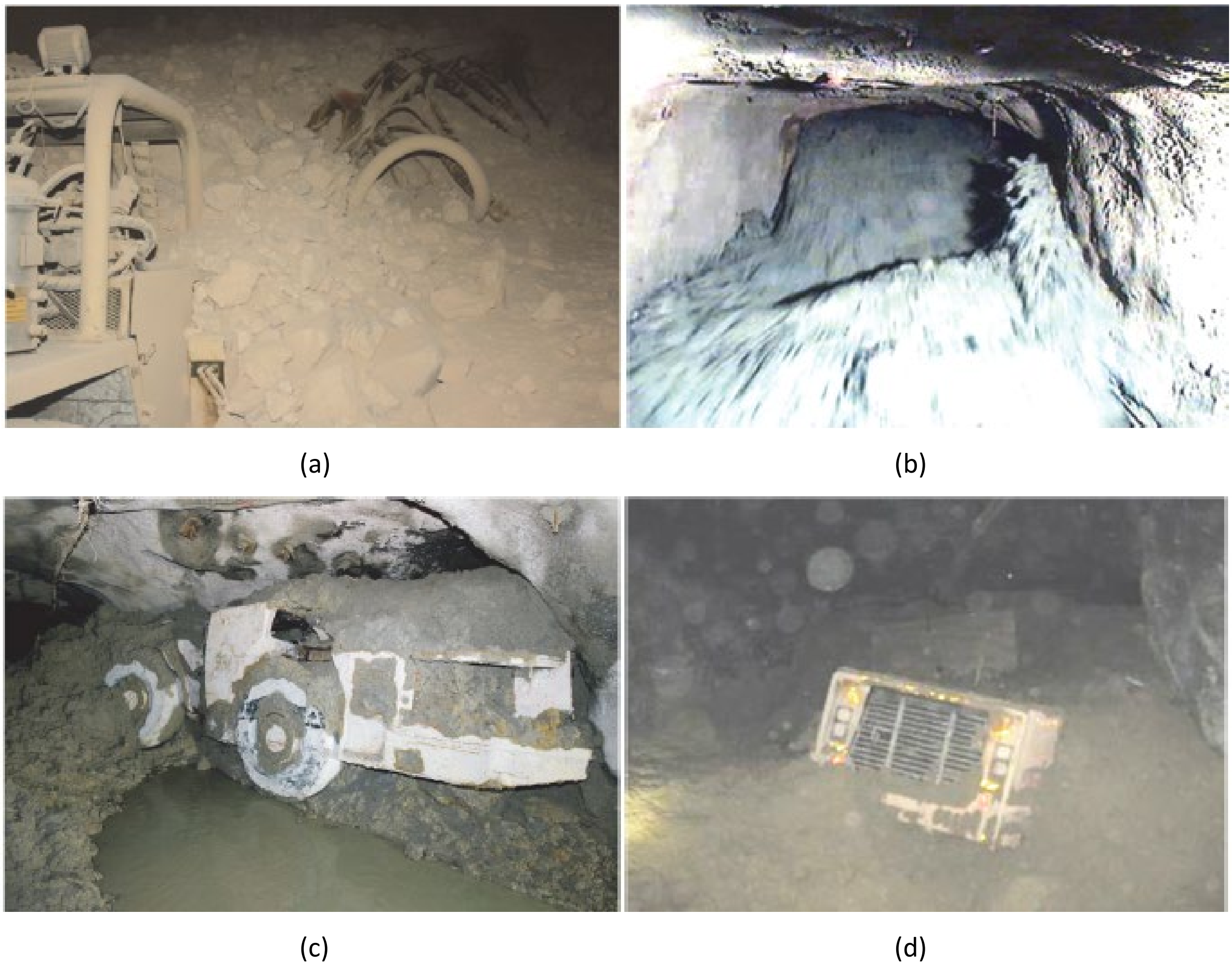


Figure 1 Inrush hazards during steady state caving. (a) Dry inrush (Long et al. 2017); (b) Water inrush (Jakubec et al. 2012); (c) Mudrush (Revuelta et al. 2008); (d) Mudrush (Widijanto 2012). Figure from Flores-Gonzalez (2019)

The requirement to monitor the contributing factors for inrush, interpret and classify the risk and then communicate to the wider workforce is commonly explicitly required under the local mining regulations (e.g. Government of New South Wales [2022] – Section 115). This is typically undertaken proactively by operations utilising inrush management plans or equivalents, and various communication avenues with site personnel, with regulatory requirements as a secondary focus to the duty of care for workers. Having the ability to monitor and interpret on a near-real-time frequency provides obvious advantages to risk management in the most high-risk operations with standardised outputs, data formats and alarm systems. The methods that different operations employ to manage inrush risk vary from the use of conventional spreadsheets through to custom solutions like that developed by Rio Tinto and Palantir (Moorcroft et al.

2022). The method implemented has obvious budget implications, and a custom software solution is not necessarily accessible to all mining operations. However, the need to implement data-driven monitoring workflows to manage inrush risk remains, and alternative solutions must be considered.

An opportunity was identified to enhance risk-management capability within the mXrap (Harris & Wesseloo 2015) platform by leveraging existing fragmentation data from the Caving Sandbox, supplemented with drawpoint observation data and site-specific risk matrices. By building on the established mXrap platform, widely used across caving operations and recognised as a cost-effective solution for geotechnical data visualisation and analysis, a low-cost, broadly accessible inrush management tool could then be developed.

1.1 Problem-based solution

To develop a solution, a clear problem definition was required. In this instance, the problem was generically defined as the inability to quickly, easily and automatically visualise the inrush hazard across an extraction level footprint, which in turn resulted in difficulties in implementing appropriate control measures in a timely manner.

As already outlined above, the critical inputs into this assessment have been established by numerous previous authors and summarised by Butcher et al. (2005) and Mussolino et al. (2024), among others, as fines percentage and water ingress at the drawpoint level along with a stimulus. Whilst fragmentation data is already incorporated into the Caving Sandbox app in mXrap, the ability to classify fragmentation in relation to inrush risk is a new feature that is required, along with the addition of drawpoint water status. This in turn highlighted the challenge of different operations having different fines thresholds, based on experience at their operation, for critical inrush risk. Similarly, categories and quantification of water status (moisture content versus inflow, with associated site-specific definitions) were other inputs that would likely have site-specific categories applied, and both features would require allowance in the solution for customisation to be integrated without too much rework.

Another challenge was ensuring that the process of inputting the data, categorising it based on predefined thresholds and assigning a risk category was as automated and standardised as possible. Not only would this support the requirement for quick and efficient visualisation of inrush hazards, but it would also minimise the potential for data entry errors and miscommunication with key stakeholders due to variable colour schemes, outputs, and interpretations.

2 App development

The app development effort was undertaken by individuals without formal training in software engineering; however, they possessed a strong interest in application development and general programming. As their primary expertise lay outside software development, designing and implementing a technical solution required a cautious, considered approach. To address this, skill development was explicitly incorporated into project planning and timelines, supported by self-directed learning, engagement with available training materials, and access to suitably qualified external technical support.

As software development is not a core function of the Resolve business, the app’s development was undertaken partly as professional development and out of interest, and partly to develop a potential component of the business model. In contrast to a typical project with an engaged third party and strict delivery timelines, this project had flexibility in its completion. The eventual project timeline is shown in Figure 2.

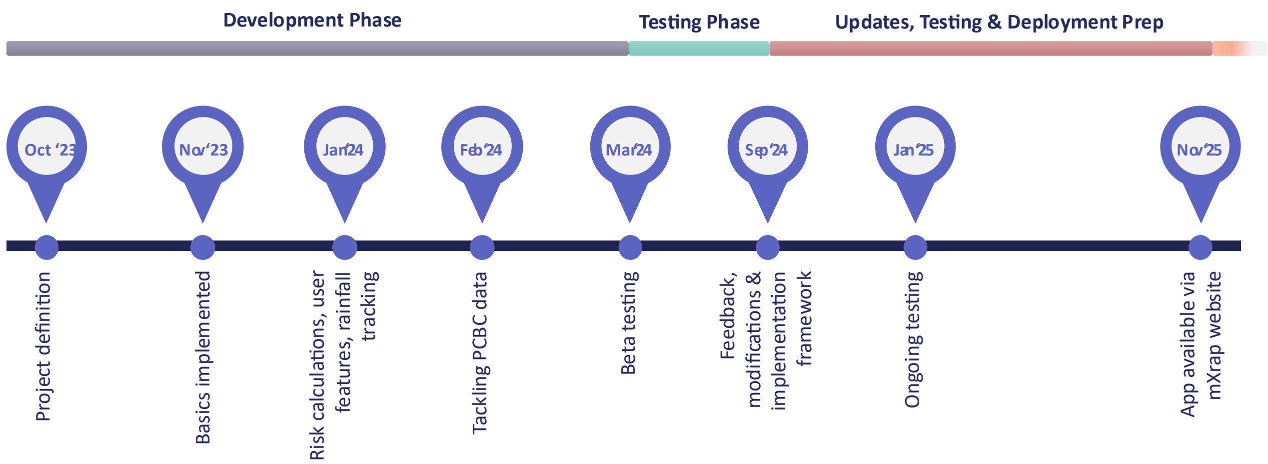


Figure 2 Development timeline for the Inrush app

Beginning in October 2023, the project from development to release for others to access via mXrap took 2 years to complete. The authors believe this is a protracted timeline, a function of competing priorities and deadlines for concurrent project work that displaced this development activity. The dedicated development of a feature like this could be halved, at least from conception to delivery, even without the underlying core skills that have since been developed.

To keep the project on track and avoid becoming sidetracked in endless possibilities, the initial development phase was focused on establishing 3 key features:

1. add in drawpoint observation data to mXrap (Figures 3 and 4)
2. create a 3D view and apply marker styles so that different marker styles can be visualised
3. enable time filtering functions so data can be progressively stepped through.

The leveraging of existing functionality and features within mXrap was also a key element of this phase because:

- Why reinvent the wheel? If there is already existing functionality available, use it.
- Utilise existing functionality as a tool to learn – with limited JavaScript experience, learning on the go was key to making progress with this project. By being able to deconstruct existing features and then apply that understanding to developing new features, learning was progressive, and less reliance on external support was needed.

To support the development of new features, a generic dataset was created along with a dummy extraction level, complete with drawpoints (Figure 3) and all the supporting data that would typically be captured and available in an mXrap Caving Sandbox on a site. The aim of this was to enable the visualisations to be created whilst maintaining flexibility for site-specific formats and inputs for use during rollout.

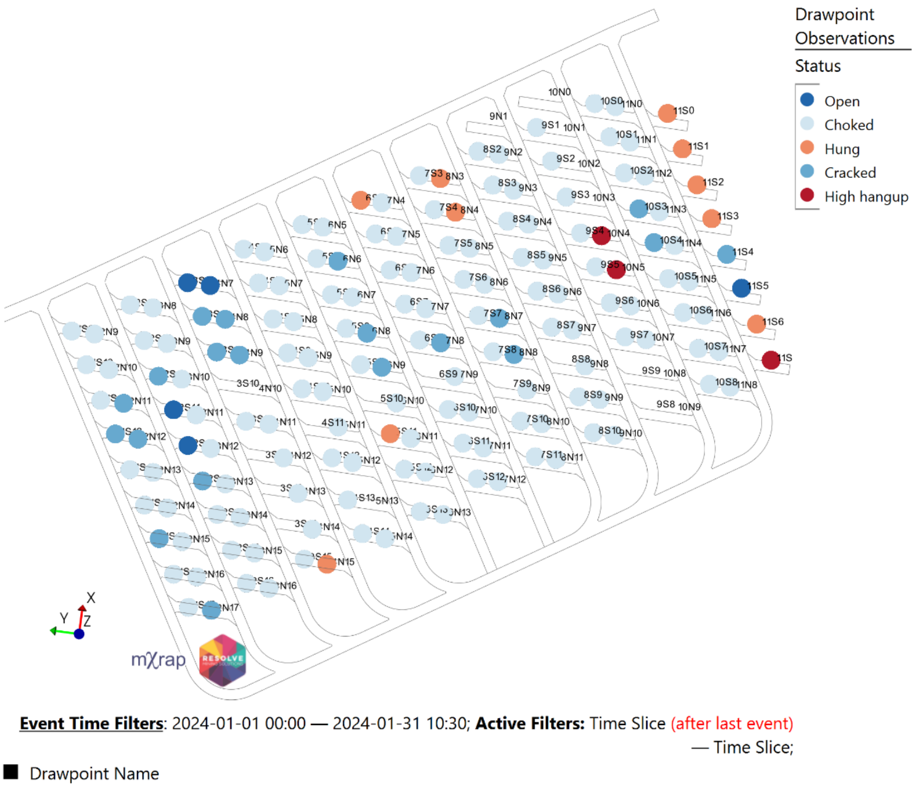
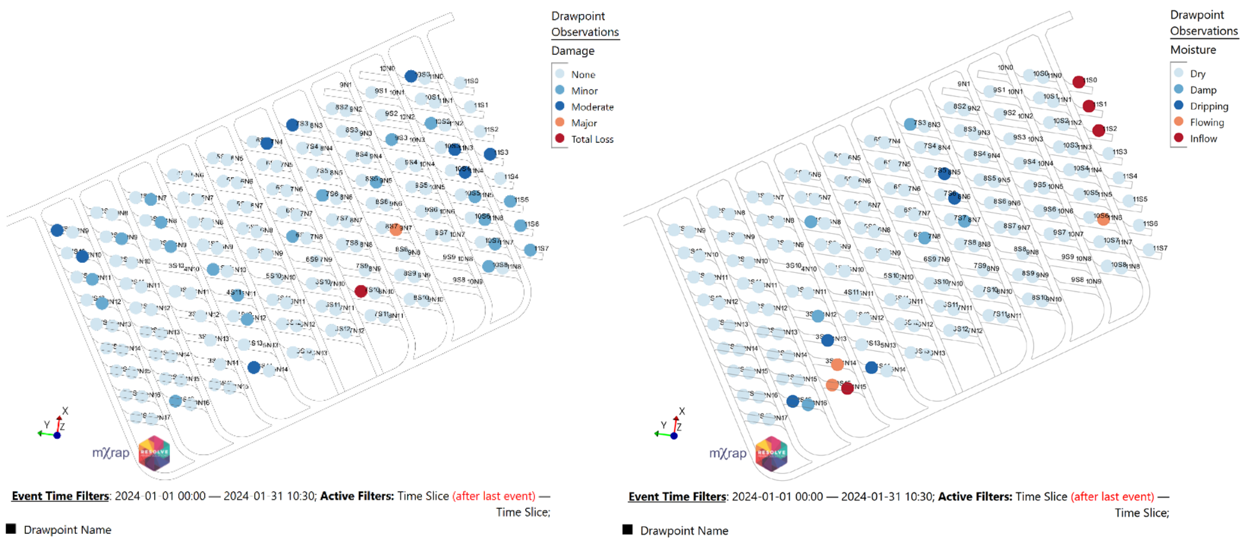


Figure 3 Drawpoint status mapping of dummy dataset and generic cave footprint

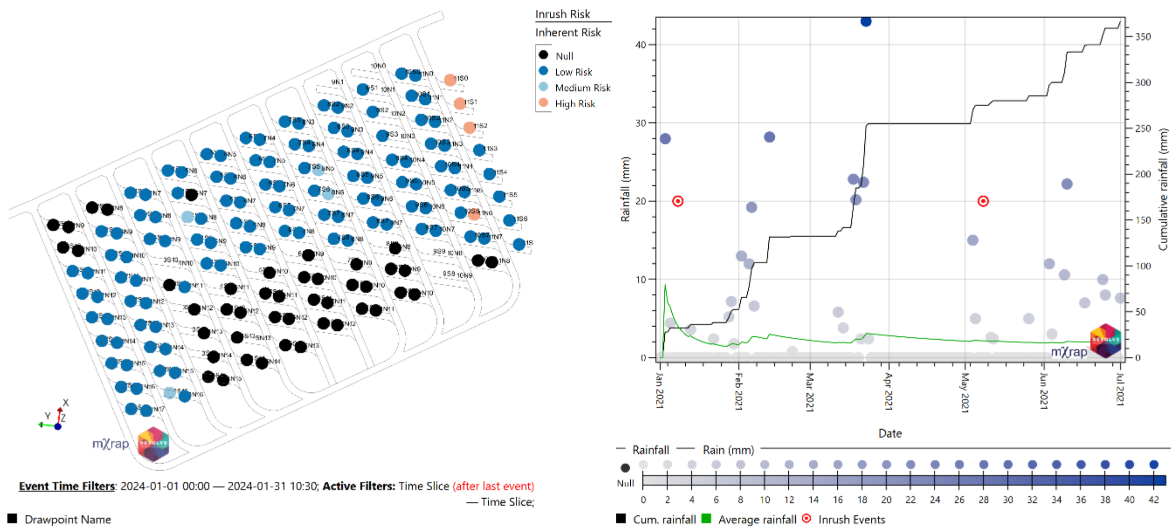


(a) (b)

Figure 4 Examples of (a) drawpoint damage plotting and (b) drawpoint moisture status

Following the development of the basic tools, a review of what aspects of the risk-management tool would be beneficial and could be implemented was undertaken, and a gap analysis was completed. Missing elements were identified, and the development phase was expanded to include:

- addition of calculated fields for risk (Figure 5a).
- addition of a definition and information page to the app landing page.
- rainfall tracking (Figure 5b).
- inrush event database.



(a) (b)

Figure 5 Visualisation of (a) inherent risk by drawpoint and (b) rainfall data, including cumulative and average rainfall

Calculating the risk also required classifying fragmentation and water status based on a predefined risk matrix and trigger levels. This was one of the features that would require customisation for any site to which the app was rolled out, to account for variability in risk matrices and input classifications, as well as critical limits defined on a site-by-site basis.

The addition of an App Information page also meant that the calculations undertaken within the app could be explicitly called out, avoiding any black box calculations, along with maintaining transparency and alignment with site-specific classifications and assessments. Whilst this doesn't impact the app's functionality, from personal experience with other software packages, having a clear understanding of what calculations are being carried out behind the scenes helps build confidence in the outputs. Additionally, it enables validation to be completed, to demonstrate the app functionality to management and external parties (e.g. Regulators) if required.

Rainfall tracking, whilst appearing straightforward on the face of it, was integrated to assist sites in understanding the relationship between the amount of rainfall and the triggering of an inrush event. By overlaying the inrush events on the same chart, the lead-lag relationship, if present, would also be easier to visualise from the same platform and feed into trigger action response plans as needed.

The final stage of the development phase saw the introduction of GEOVIA PCBC (2026) data for the mapping, visualisation and tracking of fines prediction in the app, along with graphical displays of this data (Figure 6). The intention of including predictive data was to enable proactive risk management and support the visualisation of potential risk in an easy-to-communicate way.

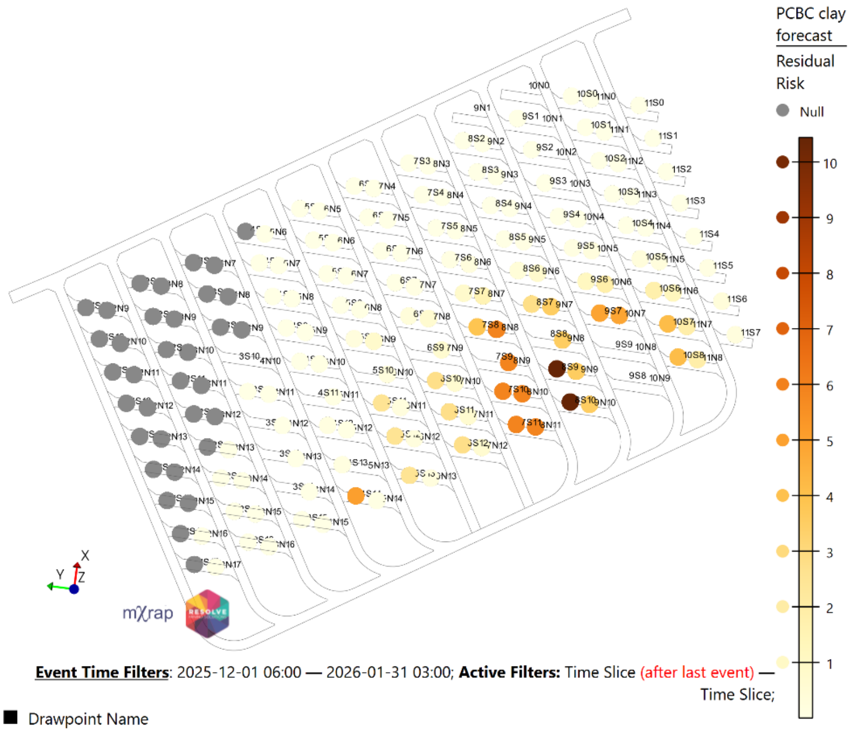


Figure 6 GEOVIA PCBC (2026) clay forecast overlain on the dummy cave footprint

One aspect of the project that developed in parallel with the original scope was ensuring accessibility for people with colour blindness. In Australia, around 8% of males and 0.4% of females experience some degree of colour blindness, and with red-green colour blindness being the most common type (Vision Eye Institute 2017), consideration for how well the colour schemes adopted in the app are communicated to the target audience was a key consideration. This is even more important when considering risk, and the conventionally adopted colour scale of red to green representing bad to good. For a male workforce of 500, 8% equates to 42 people that cannot tell purely based on colour if something on the conventional risk scale is good or bad, safe or unsafe. Figure 7 provides an indication for what someone with red-green colour blindness can see for a typical colour scale adopted frequently in mining.

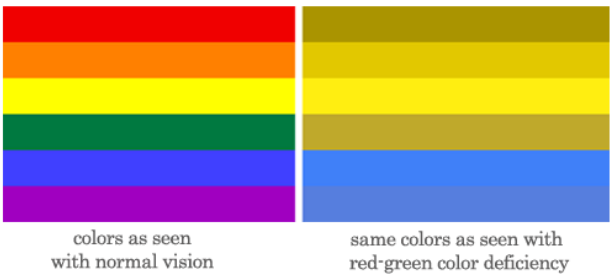


Figure 7 Visualisation of red-green colour deficiency (Colclough 2018)

Based on this, all the default colour schemes adopted in the Inrush app utilise colour-blind-friendly palettes that are either on a gradational scale which translates between both those with and without colour blindness or alternatively, the adopted colours also have sufficient contrast for both groups of people.

3 Trials

Following completion of the initial app, Resolve approached Northparkes Mines regarding undertaking a beta trial of the app with their own data. The aim of this trial was to:

- ascertain if the features developed within the app are functional and useful at an operational level
- identify opportunities for improvement
- understand what is required for distributing the app to interested parties

The intent was for the trial to run for a 6-month period with regular check-ins to identify any challenges. This trial was subsequently extended to 12-months to provide additional trial time and update of some key features.

There were several key lessons learnt during this rollout which would then be implemented in version updates and in preparation for the app launch. This trial also highlighted the key information required to be distributed along with the app to ensure that the functionality and features would be understood and the calculations are suitable for the specific site, and that any customisations and buy-in from key stakeholders was achieved at the rollout stage.

Another key learning for the Resolve team included understanding how to execute an effective app rollout. Having only been on the receiving end of updates previously, understanding the requirements for locking of certain features to prevent accidental editing which would impact functionality of the app, documentation to support the rollout and what templates and settings need to be defined to streamline the deployment was all new to the team.

Ultimately, the trial rollout was effective, and the initial functionality within the app was met with good feedback, and excellent suggestions for future upgrades and functionality expansion. Future development features included the generation of heatmaps of risk, comparing predictions and actual observations of fines to support GEOVIA PCBC (2026) calibration, drawpoint differential calculation, integration with PCGA (Power Geotechnical Cellular Automata software, 2026) and a dashboard to highlight time since last data entry. For non-database-linked data sources, this would provide a simple interface to trigger further data capture or upload to support the risk-management efforts. These features have been added to a development checklist and will be implemented in future releases of the software.

4 Deployment preparation

Following development and the successful trial of the Inrush app version 1.0, the next key step in the project was understanding requirements for deployment and launch. Whilst the app was intended to be commercialised once developed for a negligible fee, to officially launch it and deploy to interested license holders, 2 key steps required completion:

- app bundling
- preparation of marketing material.

Bundling is a process of grouping key settings files, calculations, legends, layouts and other app features that do not require modification and whose functionality is key to the overall performance of the app. Once isolated from the other files that do require editing, these files are protected by a series of security settings resulting in an app which is then safe from accidental edits or from modification by others. It provides a layer of confidence that the basic performance of the app cannot be modified without interaction with the developer and protects the output of the various developed features. It also ensures that updates made by the developer can be rolled out efficiently whilst avoiding extensive conflicts and potential loss of functionality.

Whilst it sounds simple in theory, the process of identifying the required files for bundling can be iterative and requires testing to ensure that key files that do need to be edited by the end user are not included in the bundling process and vice versa. This step was also key to ensuring protection of intellectual property and enabling access limitations by license keys, all of which could then be managed in the same way as other mXrap applications.

Preparation of marketing material and information for the user on the functionality, features and supporting data requirements was also a key step prior to launch and deployment of the Inrush app. Whilst this was more familiar territory, alignment with the existing document styles, content and structure was required to maintain consistency with the broader mXrap platform.

5 Future development opportunities

In addition to the features highlighted in Section 3, several additional development areas were identified throughout the project.

5.1 Integration with operational software

Production systems like Deswik ORB or Pitram provide application programming interfaces (APIs) and import/export methods that provide an opportunity for integration with this mXrap data. Because of the simple data structures contained within the Inrush app, mapping the data between these systems would be considered relatively trivial.

The most direct value of such an integration would be the continuous, either scheduled or real-time, updating of safe drawpoint status. Such a configuration would enable these production systems to highlight to operational staff any at risk drawpoints. If required, dispatch of personnel or manually operated equipment to any drawpoint that has reached a specific threshold can then be prevented. Doing so would enforce geotechnical instructions, which otherwise may only be provided as written or verbal instructions to the operational team.

The flexibility of the mXrap suite also enables a transfer of information from these operational systems. Often, sites will leverage operational staff to provide observations of the underground conditions, so these can directly feed into the Inrush app, rather than waiting for predefined entries from the geotechnical team. Whilst such an integration has not yet been made, it is expected that there would be some verification process involved to ensure untrained observations which are inherently inconsistent do not unnecessarily constrain the system or produce ‘garbage’ results.

5.2 Data validation and checks

Ensuring that data used for risk determination has undergone appropriate quality assurance and quality control supports the overall effectiveness of the site safety management system. To improve robustness, future developments in the Inrush app are planned to incorporate automated validation tools, including duplicate detection, data format checks prior to import, and range checks to prevent data entry errors (for example, verifying that fragmentation percentages sum to 100%). Implementing these controls at the data import stage prevents contamination of existing datasets and ensures that high-quality outputs are generated from validated inputs.

5.3 Integration with automatic fragmentation tracking data

With automatic fragmentation tracking advancing in recent years and being trialled in caving operations (Thurley et al. 2015; Liu et al. 2015; Brunton et al. 2016; Pierce et al. 2020; Yang 2025), it is only a matter of time before the handling of large fragmentation datasets in the risk-management environment is required. Automatic linking to SQL databases is already feasible within the mXrap framework and integrating this functionality into the Inrush app and back into the production software is a logical next step for development. This would also assist users in the handling of large datasets as any required filters, accumulations, statistical analyses, etc. can be standardised and integrated into the app, avoiding potential for user error and maintaining a consistent output.

6 Conclusion

The process of taking an initial "wouldn't it be nice if…" idea and turning it into reality was a positive learning and development experience for those involved and enabled the development of a solution that has the potential to assist caving operations with understanding and visualising their inrush risk. Utilising the existing mXrap framework and with support from the Australian Centre for Geomechanics mXrap team, not only was an application able to be built with the key primary features that the authors intended, but a plan for future development, pending interest and uptake, could be outlined.

Without any formal software engineering or programming qualifications, backed only by a keen interest and self-driven desire to learn and deliver a solution to a challenge experienced by the authors, an app was constructed, tested and launched over a 2-year period. It is the belief of the authors that the time taken for development could have also been significantly reduced if dedicated resources had been available. For others interested in also developing an app, don't assume that because you're not a programmer it isn't possible. This project has demonstrated that it is feasible and can successfully result in a functional app that can add value, be it across the industry or locally to solve a specific challenge at your operation.

What began as a personal interest was successfully developed into an application that is now available to a wider group of users. The project objectives were achieved, delivering both a functional outcome and significant professional development. More importantly, the project demonstrates that individuals with a genuine interest and initiative can develop practical tools to streamline day-to-day site tasks, and it is hoped this experience will encourage others to pursue similar improvements.

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