Tailings storage facilities flood exposure assessment using a 2D hydrodynamic model

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Abstract
Minimizing environmental pollution from Tailings Storage Facilities (TSFs) is one of the key goals of the mining sector. While much attention is given to risks from potential catastrophic failures of large TSFs, there is also a need to assess risks due to noncatastrophic but more frequent releases of contaminants. In response to this need, this article proposes a method for prioritizing TSFs in terms of flood exposure, based on flood maps produced by the Shallow Water Integrated Flood Tool. The method was implemented using a case study of a flood event in the Copiapó/C19o city region (Atacama, Chile). A sensitivity analysis was carried out to evaluate the influence of different model configurations and input parameters. The results showed that 10% of all the TSFs in the case study region were exposed to flood waters due to the fluvial dynamics of the Copiapo River. Additionally, the sensitivity analysis revealed that in the event of extreme local precipitation, capable of generating runoff, up to 88% of all the TSFs could have some degree of flood exposure. The results also suggest that flood simulations using satellite-derived terrain data at moderate resolution can be used for a preliminary large-scale assessment of TSF flood exposure.

Keywords
contaminated land, extreme events, mapping of flood hazards, SWIFT, TSFs

1 | INTRODUCTION

Tailings, a by-product of mineral processing, are stored in structures commonly referred to as Tailings Storage Facilities (TSFs). TSFs are commonly constructed in incremental steps over the life span of a mining project (Lottermoser, 2010; Pastor et al., 2002) and their retainment structure is usually constructed using the coarse fraction of the tailings (Villacencio et al., 2014). In some cases, tailings particles contain high concentrations of hazardous pollutants such as arsenic (Liu et al., 2010), cyanide (Bakatula & Tutu, 2016; Donato et al., 2007), heavy metals (Johnson et al., 2016; Lottermoser, 2010) and depending on the extracted commodity, even traces of radioactive elements (Landa, 2004; Winde & Walt, 2004). Tailings-borne contaminants can be released into the atmosphere as dust particles (Csavina et al., 2012) or into surface waters as suspended particles or dissolved species (Andrade et al., 2006). When eroded from TSFs, tailings particles can reach...
crops (Grimalt et al., 1999; Mileusnić et al., 2014),
humans (Ngole-Jeme & Fantke, 2017)
and other living organisms in nearby ecosystems
(Boening, 2000; Kiser et al., 2010; Nriagu et al., 1998).
During the last decades, numerous studies have evaluated acute water contamination
derived from catastrophic failures of large tailings
dam (e.g. Byrne et al., 2018; Rico et al., 2008;
Soldán et al., 2001). Much fewer have assessed contamination
of fluvial systems due to pluvial and fluvial erosion of TSFs,
especially in historic mining regions (e.g. Coulthard &
Macklin, 2003; Dennis et al., 2009; Martín Duque José
et al., 2015; Pavlowsky et al., 2017). Erosion of TSFs is a
Cumulative process that happens over decades or even
centuries (Kincey et al., 2018; Knittel et al., 2005; Lecce &
Pavlowsky, 2014). Moreover, pluvial and fluvial erosion
of TSFs will almost certainly increase in coming years
due to the intensification of precipitation and floods due
to climate change (Prein et al., 2017; Tabari, 2020).

When runoff or floodwaters reach the surface of TSFs
a shear force is produced (Gallart et al., 1999).
This shear force depends on the flow characteristics (velocity and
depth), and its erosion potential depends on tailings character-
istics such as particle size and inter-particle cohesive forces
(Geremew & Yanful, 2010; Yanful & Catalan, 2002). On other hand, infiltration of rainfall and
runoff into the TSF can increase the pore pressure acting
on the retention structure, affecting stability and suscep-
tibility to future erosive forces (Blight & Fourie, 2005).
Additionally, the saturation of TSFs due to flooding can lead to leaching of dissolved contaminants into surface
waters (Castro-Bolinaga et al., 2014; Concas et al., 2006).
These pluvial and fluvial interactions are schematically
summarized in Figure 1a.

The assessment of environmental risks due to long
term erosion of TSFs is commonly approached following
three steps: (1) modelling of erosive forces and quantifi-
cation of eroded volumes (e.g. Chunjuan et al., 2020;
Kincey et al., 2018; Slingerland et al., 2020); (2) evaluation
of the TSF’s pollution potential (e.g. Schanze, 2006;
Nasiri et al., 2016; Liang et al., 2017); and (3) evaluation of pol-
lution consequences (e.g. Ngole-Jeme & Fantke, 2017).
These steps commonly involve laboratory analysis of
samples taken from downstream surface water, groundwater, soil, sediments and tailings. In the case of histori-
cal regions with multiple TSFs, it is not easy to undertake
a comprehensive risk assessment, due to the high cost
particularly for sampling and laboratory analysis. On the
other hand, in recent years computer-based flood mapping
techniques have been proposed as a valuable
approach to understanding and mitigating the potential

FIGURE 1  (a) Conceptual model of flood erosion of tailings dams and abandoned tailings piles located on river floodplains.
(b) Schematic representation of buffer zones used in this article for the quantification of the TSF proximity to floods.
effects of floods at local and regional scales (e.g., Gouldby et al., 2008; Lamb et al., 2010; Merz et al., 2007; Su et al., 2005). Therefore, the use of computer-based flood mapping approaches can help to prioritise sites that warrant a comprehensive risk assessment that would include all three steps listed above.

Currently, there are multiple approaches to flood mapping with different levels of complexity and precision (Anees et al., 2016; Hunter et al., 2007; Teng et al., 2017). However, flood mapping tools that implement hydrodynamic principles are regarded as the industry standard for flood risk assessment (e.g. Bates & de Roo, 2000; Horritt & Bates, 2002). The most common hydrodynamic approach for flood mapping consists of 1D and 2D simplifications of the Navier–Stokes Equations, principally the Shallow Water Equations (Néelz & Pender, 2013; Anees et al., 2016; Costabile et al., 2017; Teng et al., 2017; Savant et al., 2019). Different limiting factors, including computational feasibility and the problems of accurately representing the water free surface, high-order turbulence and transient flood shoreline make it difficult to implement a complete numerical solution of the Navier–Stokes Equations, justifying the implementation of different simplifications (Hunter et al., 2007). These flow approximations reduce computation times at the expense of accuracy in the flow height and flow velocity predictions (Bout & Jetten, 2018). The Shallow Water Equations assume that 2D flow over an inundated floodplain is a slow, shallow phenomenon in which the assumption of hydrostatic pressure with the free surface boundary condition eliminates the depth-wise component of velocity (Kurganov & Petrova, 2007). These hydrodynamic models are commonly implemented in urban and coastal environments where detailed topographic data are available in the form of Digital Terrain Models (DTMs) (e.g. Fewtrell et al., 2011; Meesuk et al., 2015). Unfortunately, historical mining regions are commonly located in remote areas where high-resolution DTMs are not readily available. Furthermore, TSFs in historical mining regions are commonly spread over large areas making it impractical to run hydrodynamic models at a high spatial resolution (5 m or less) due to the high computational demands. This article aims to assess the suitability of a 2D hydrodynamic model for conducting a rapid assessment of TSF flood exposure in a historical mining region; and to identify the model settings that provide a useful balance between computational cost and accuracy of TSF flood exposure results.

The first subsection of the Methods (Section 2.1) introduces the reader to the case study area, while Section 2.2 presents the proposed flood modelling tool (SWIFT). Following this, Section 2.3 presents the method for prioritizing TSFs. Then, Section 2.4 describes a model sensitivity analysis and Section 2.5 defines the model evaluation metrics. Finally, Section 4 presents Results and Discussion and Section 5 the Conclusions.

2 MATERIALS AND METHODS

2.1 Case study region

Northern Chile hosts the Atacama Desert, one of the driest nonpolar regions of the world. Despite being a predominantly arid region, climate anomalies such as cut-off low pressure systems, the Madden–Julian oscillation, and El Niño Southern Oscillation can cause extreme precipitation and unexpected floods and mudflows (Houston, 2006; Ramirez & Perez, 2011; Rojas et al., 2014). Between the 24th and the 28th of March 2015 a catastrophic flood event occurred in Copiapó city (Figure 2) due to the overflow of Copiapó river (Figure 2) and its tributary Quebrada Paipote (Bozkurt et al., 2016; Fernández & Espinoza, 2020). During this event a total cumulative precipitation depth of 22.7 mm over a period of 72-h between the 24th and the 27th of March 2015 was registered at the Copiapó city rain gauge, with totals up to 86 mm registered at stations further up the catchment (Fernández & Espinoza, 2020). Despite being a low magnitude precipitation event on a global scale, the arid conditions, inadequate drainage and the lack of preparedness caused devastating floods with great economic losses (Bronfman et al., 2019). After this flood event the Chilean Ministry of Housing and Urban Planning surveyed flood levels and mud levels at different locations around the urban and peri-urban areas of Copiapó city. Figure 2b shows selected water depth observations used for the calibration and evaluation of the 2D hydrodynamic model in the present study.

Copiapó River Basin has multiple abandoned and inactive TSFs that have been left behind after a long history of mining of copper and gold deposits in this region. Many of these are located on the lower floodplains of Copiapó River and its tributaries (see Figure 2). Additionally, recent studies have highlighted the importance of further research focused on risks associated with extreme flood events in the basin (Falconcón et al., 2017; Izquierdo et al., 2020). For these reasons, Copiapó city and its peri-urban areas (modelling extent shown in Figure 2b) are an interesting case study for this research. The studied region comprises a rectangle of 138 km² that contains 75 TSFs out of the 118 TSFs registered for the entire Copiapó River Basin (SERNAGEOMIN, 2020). The coordinates, operational status, construction method and the storage capacity of each TSF inside the modelling domain are presented in Table A1. These 75 TSFs are
heterogeneous in terms of age, physical characteristics, construction method and geochemical composition, ranging from modern tailings dams with high engineering standards (16-AC) to legacy mine waste deposits (abandoned tailings piles) lacking ownership (e.g., 1-AB, 2-AB and 3-AB). Additionally, most of these TSFs do not have a protective surface layer and have not undergone a formal rehabilitation process (Carkovic et al., 2016; Soublette et al., 2011), which makes them more susceptible to erosion. Finally, the selected area is of interest for environmental and mining authorities due to the proximity of these TSFs to human settlements and agricultural land along Copiapó River valley.

2.2 Model description

2.2.1 SWIFT

The Shallow Water Integrated Flood Tool (SWIFT), developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), has been selected for this study since it was previously calibrated and validated in the selected case study region by Claro et al. (2018). Additionally, SWIFT has been benchmarked against different well-known inundation models (Cohen et al., 2016; Prakash et al., 2020), demonstrating its suitability for addressing different aspects of flood modelling as described by Néelz and Pender (2013). SWIFT solves the 2D Surface Water Equations (Equations 2–4) by discretising the modelling domain into a rectangular grid and using a positively preserving, finite-volume solution, as described by Cohen et al. (2015).

\[
\frac{\partial (w-B)}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0
\]  

\[
\frac{\partial q_x}{\partial t} + \frac{\partial}{\partial x} \left[ \frac{q_x^2}{w-B} + g \cdot \frac{(w-B)^2}{2} \right] + \frac{\partial}{\partial y} \left[ q_y \cdot \frac{(w-B)}{w-B} \right] = -g \cdot \frac{(w-B)}{B_x} 
\]  

\[
\frac{\partial q_y}{\partial t} + \frac{\partial}{\partial x} \left[ q_x q_y \right] + \frac{\partial}{\partial y} \left[ \frac{q_y^2}{w-B} + g \cdot \frac{(w-B)^2}{2} \right] = -g \cdot \frac{(w-B)}{B_y} 
\]

where \( q_y \) and \( q_x \) are discharge rates (m^2 s^{-1}), \( B_x \) and \( B_y \) encompass the base slopes and losses due to friction in the \( x \) and \( y \) directions, \( B \) is the vertical height of the terrain from a specific datum (m), and \( w \) represents surface water depth (m). SWIFT allows for time-varying

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**FIGURE 2** (a) Location of Copiapó River basin and location of tailings storage facilities (TSFs) as reported by Servicio Nacional de Geología y Minería (SERNAGEOMIN, 2020). (b) Location of TSF polygons classified according to the type of retention structure (dams in depicted as black polygons and embankments as magenta) and location of flood height observations after event of March 2015 (green squares). TSF polygons labeled according to operational status (Active = AC, Inactive = IN, Abandoned = AB).
boundary conditions, varying floodplain roughness and the inclusion of different hydraulic structures along the main channel such as bridges and levees (Hilton et al., 2015; Prakash et al., 2015). SWIFT is also capable of integrating high-resolution Digital Terrain Models (DTMs) along the river channel with moderate and low-resolution Digital Elevation Models (DEMs) for the river’s floodplain. Additionally, SWIFT allows the inclusion of urban drainage infrastructure by coupling the 2D surface model with a hydraulic pipe network. SWIFT is also capable of modelling rainfall using the rain-on-grid approach and infiltration through the application of the Green and Ampt model for each cell in the modelling domain. The following subsection will discuss the limitations in the application of the different components of SWIFT in the case study region as well as the description of the different input data used to simulate the flood event of March 2015.

2.2.2 Limitations in SWIFT’s applicability and input data

The input parameters calibrated by Claro et al. (2018) for the event of March 2015 are presented in Table 1. These inputs were selected to resemble the observed flood event. The terrain data used in this study consisted of several DEMs, supplied by the local authorities, covering the modelling domain at different cell resolutions ranging from 1.6 m to approximately 30 m. These terrain datasets were generated using a combination of lidar scans and surveyed control points to tie them to the correct vertical datum (Claro et al., 2018). These DEMs were composited together by SWIFT’s solver so that the best quality dataset (from finest resolution to coarsest) was used at each point of the grid. This flood event had a low probability of annual exceedance (<2%) according to the frequency analysis carried out by Valdés-Pineda et al. (2017). The modelled flood maps and the flood heights obtained with these model inputs were comparable to those obtained for the same flood event by Valdés-Pineda et al. (2017) and Izquierdo et al. (2016).

Although the model is capable of modelling the interconnection of surface flow with Copiapó’s drainage network, this feature was not included in the present case study due to the relatively low magnitudes of sub-surface drainage compared with the peak flows of the input hydrographs (Claro et al., 2018). The rainfall losses due to infiltration were also not accounted for in the calibration of the model by Claro et al. (2018) due to the relatively high inflows from the catchment, relatively small, modelled area and imperviousness of much of the urban area. However, infiltration capacities in arid regions can be high, for example an average saturated hydraulic conductivity of 78 mm/h has been reported for hillslopes in the Atacama (Pfeiffer et al., 2021), which is much higher than the maximum hourly rainfall used for the rain-on-grid option (3 mm/h). Therefore, the accumulation of surface runoff due to local rainfall is likely to be minimal, hence the rain-on-grid results are considered to be an upper bound to pluvial flooding extent under this event.

2.3 Evaluation of model performance and selection of a benchmark

The ability of the model to adequately reproduce flood observations was evaluated through the metrics presented in Table 2. The RMSE quantifies the average water level error, while the other two metrics quantify the flood extent accuracy and the percentage of model overpredictions relative to the observed flooded areas (e.g., Sampson et al., 2015; Stephens et al., 2014; Wing et al., 2017). These metrics were evaluated using different model settings, terrain sources and treatment of rainfall and bridges as described in Table 4. The simulation identified in Table 4 as S-03 was selected as the “benchmark” configuration following the recommendation of Claro et al. (2018), who found that this simulation best represents the 2015 flood by including the blockage of two bridges in the urban reach of the Copiapó River and by optimising the values of RMSE. The purpose of the benchmark is to report the sensitivity of flood exposure and other model outputs in relative terms, and it is not assumed that this is the preferred model for assessing TSF flood risk.

The terms SWE$_{obs}$ and SWE$_{pred}$ in Equation (4) represent the observed water elevations and the modelled water elevations at the selected observation points surveyed by the local authorities after the flood event of 2015 (see Figure 2b). The terms A, B and C in Equations (5) and (6) represent a crossed error scheme where: A is the percentage of flooded areas correctly predicted by the model (hits), B is the percentage of areas predicted as flooded that are dry according to the observations (over-prediction/ false positives), and C is the percentage of flooded areas not predicted as flooded by the model (under-prediction/misses).

2.4 Flood exposure assessment of TSFs

The TSF flood exposure was quantified using a Flood Exposure Index (FEI) with units m$^2$ s$^{-1}$. This quantity aims to encompass the key topographic and hydraulic factors affecting TSF vulnerability to floods:
where FPI corresponds to the Flood Proximity Index (−), FH corresponds to flood height (m) and FV corresponds to flood velocity (m s⁻¹). The product of FH and FV is the Flood Hazard, and its maximum value at each cell through the entire simulation was calculated only when the flood height exceeded 0.1 m. The FPI was determined by overlaying the flood predictions with different buffer polygons representing the proximity of TSFs to flood-prone areas as described in Table 3 and shown schematically in Figure 1b. This GIS-based approach for quantifying flood exposure of mine waste deposits was based on the method proposed by Neuhold and Nachtnebel (2011). The TSF polygons were delineated manually based on the coordinates provided by the
national database of tailing storage facilities (SERNAGEOMIN, 2020) and satellite imagery provided by the base map service of ArcMap (Esri, 2020). Maximum FV and FH values were extracted from SWIFT's results for each TSF polygon. The inner buffer distance of 15 m corresponds to twice the average pixel resolution of the satellite imagery used for delineating the TSF polygons. The buffer distances of 30 and 60 m were selected to be equal to the median and the average TSF radius for the case study area.

### 2.5 Quantification of flood exposure index and its sensitivity to model settings

The sensitivities of FEI to different terrain sources, DEM settings and treatment of rainfall and bridges were evaluated through the 13 simulations listed in Table 4. These simulations were grouped into four different categories to evaluate the influence of: (a) simulation resolution; (b) terrain and channel features; (c) terrain data source; and (d) rainfall-runoff processes. The influence of simulation resolution was evaluated by running SWIFT at four different grid sizes: 2.5, 5.0, 12.5, and 30 m. The influence of terrain data sources was evaluated using three different data sources: (1) a high resolution DTM mosaic as described by Claro et al. (2018); (2) the 12.5 m resolution ALOS-PALSAR RTC product (JAXA/METI and ASF, 2007); and (3) the 30 m resolution SRTMGL1 product (LP-DAAC and NASA, 2014). The ALOS-PALSAR product was chosen due to its effectiveness for extracting drainage network features in ephemeral river basins (Niipele & Chen, 2019), while the SRTMGL1 product was selected due to its widespread use for evaluating the suitability of freely available moderate resolution DEMs for flood hazard assessment (e.g. Domeneghetti, 2016; Sanders, 2007). Finally, the influence of rainfall inclusion and the relevance of rainfall-runoff processes were evaluated by running SWIFT using uniform rainfall across the entire modelling domain for all simulations except for S-09 and S-11.

To supplement the FEI, the Relative Exposure Variation (REV) was defined to measure the variation of exposure numbers of each simulation against the benchmark simulation. The REV is the percentage of TSFs identified as exposed that are also identified as exposed by the benchmark simulation. In a similar way, a metric called Relative Computational Time (RCT), was introduced to calculate the ratio between the computational time of each simulation against the computational time of the benchmark simulation. Finally, the sensitivity of TSF exposure was analysed with respect to changes in the highest ranked TSFs in terms of FEI.

### 3 RESULTS

#### 3.1 Model performance

The performance metrics for the different simulations are presented in Table 4. In this table, it can be observed that simulations S-03 and S-04 have the lowest values of RMSE and the highest values of CSI. Figure 3a shows the FPI values obtained using the observed flood extent and Figure 3b the simulation selected as the benchmark (S-03). The results obtained with the observed flood extent map suggest that at least four TSFs are in areas considered flooded or fully exposed to flood waters (FPI = 1.0), while another three TSFs are located in areas partially exposed to flood waters (0 < FPI < 1.0). The results obtained with SWIFT for S-03 suggest that under the...
| Simulation ID | Bridges | Buildings | Rainfall included? | Terrain data | Simulation resolution (m) | Total number of simulated cells | RMSE (m) | CSI | FAR (REV) (%) | Computation time* (CT) (h) |
|--------------|---------|-----------|--------------------|--------------|--------------------------|-------------------------------|----------|-----|----------------|---------------------------|
| S-01         | blocked | Raised    | Yes                | High-res DTM | 2.5                      | 2.21E+07                     | 1.51     | 0.29| 0.31          | 96                        | 161.6                     |
| S-02         | cleared | No        | Yes                | High-res DTM | 5.0                      | 5.52E+06                     | 1.66     | 0.22| 0.35          | 100                       | 12.3                      |
| S-03         | blocked | Raised    | Yes                | High-res DTM | 5.0                      | 5.52E+06                     | 1.41     | 0.30| 0.32          | 100                       | 12.3                      |
| S-04         | cleared | Raised    | Yes                | High-res DTM | 5.0                      | 5.52E+06                     | 1.40     | 0.30| 0.32          | 100                       | 12.4                      |
| S-05         | blocked | No        | Yes                | High-res DTM | 5.0                      | 5.52E+06                     | 1.43     | 0.22| 0.35          | 100                       | 12.4                      |
| S-06         | blocked | Raised    | Yes                | High-res DTM | 12.5                     | 8.84E+05                     | 1.42     | 0.28| 0.43          | 80                        | 1.8                       |
| S-07         | cleared | No        | Yes                | High-res DTM | 12.5                     | 8.84E+05                     | 1.53     | 0.21| 0.45          | 80                        | 1.8                       |
| S-08         | blocked | Raised    | Yes                | High-res DTM | 30                       | 1.54E+05                     | 1.49     | 0.22| 0.55          | 71                        | 0.2                       |
| S-09         | cleared | No        | No                 | High-res DTM | 5.0                      | 5.52E+06                     | 1.42     | 0.32| 0.13          | 16                        | 8.6                       |
| S-10         | cleared | No        | Yes                | ALOS-PALSAR RTC | 12.5                     | 8.81E+05                     | 2.33     | 0.28| 0.41          | 69                        | 2.0                       |
| S-11         | cleared | No        | No                 | ALOS-PALSAR RTC | 12.5                     | 8.81E+05                     | 2.26     | 0.26| 0.28          | 13                        | 1.5                       |
| S-12         | cleared | No        | Yes                | ALOS-PALSAR RTC | 12.5                     | 8.81E+05                     | 2.22     | 0.27| 0.40          | 69                        | 2.1                       |
| S-13         | cleared | No        | Yes                | SRTMGL1       | 12.5                     | 8.84E+05                     | 2.61     | 0.24| 0.53          | 78                        | 2.0                       |

*Computational times obtained using SWIFT's GUI version for Windows on a desktop computer with an Intel Xeon 2146 CPU (32 GB of RAM) and nVIDIA Quadro P2000 GPU (5 GB of RAM with 1024 CUDA Cores).
assumption of no infiltration up to 27 TSFs could be fully exposed to flood waters (FPI = 1.0), while another 18 TSFs could be partially exposed to floodwaters (0 < FPI < 1.0). Most of these TSFs identified as exposed to flood waters are located more than 500 m away from the main streams (Copiapó River and Quebrada Paipote), suggesting that their flood exposure is due to runoff along the minor surface drainage network or the accumulation of rainfall in terrain sinks (Figure 3b). Further discussion and analysis of TSF flood exposure will be presented along Section 4 and the following subsection (Section 3.2).

3.2 | TSF flood exposure and comparison against benchmark

Figure 4 shows the results of the exposure analysis and performance against the benchmark simulation grouped by: (a) simulation resolution; (b) inclusion of channel and terrain features; (c) quality of terrain data; and (d) rainfall-on-grid inclusion. It can be observed that the simulation resolution and the inclusion of rainfall-on-grid have the largest influence on the computation times (Figure 4a and d, respectively), while the inclusion of channel and terrain features have little impact on the computation times (Figure 4b). On the other hand, increasing the grid size and neglecting the rainfall run-off processes reduce the number of TSFs identified as exposed (Figure 4a,d).

Additionally, it can be observed that the simulations run using moderate resolution DEMs can identify between 69% and 78% of the TSFs classified as exposed by the benchmark simulation, while reducing the computation time by 86% to 89% (see Figure 4c). On the contrary, the inclusion of terrain and channel features has little impact on the identification of TSFs exposed to floods and computation time (see Figure 4b). The effects of simulation resolution and terrain features will be further analysed in Sections 4.1 and 4.2, while the incidence of terrain data source and rainfall-on-grid inclusion (infiltration) will be discussed in Sections 4.3 and 4.4.

Finally, Table 5 shows the ranking of the top five TSFs in terms of the magnitude of Flood Exposure Index (FEI) for the same four groups of simulations displayed in Figure 4. This table helps to understand the factors affecting the ability of the model to prioritise TSFs in terms of flood exposure. It can be observed that TSFs 1-AB, 16-AC, 24-IN, 36-IN, 39-IN, 59-IN and 60-IN are consistently identified amongst the highest priority by most of the modelling experiments. The flood maps and the TSF exposure maps corresponding to the results in Table 5 are in Figures A1 to A4.

4 | DISCUSSION

4.1 | Influence of simulation resolution

Based on the results presented in Figure 4, it can be concluded that as simulation resolution increases (pixel size decreases), all other factors being equal, the flood extent...
predictions generally improve (higher CSI and lower FAR). However, the lowest RMSE and the highest CSI are obtained with a simulation resolution of 5 m. Additionally, it can be observed that in Table 5A the FEI magnitudes change with the simulation resolution, suggesting a grid-size-dependence of flow depth and flood velocity predictions. This dependency can be caused by the misrepresentation of river channels and the floodplain landforms as the grid resolution increases as further exemplified in Figure 5. This figure shows changes in the terrain representation of landforms such as TSFs when increasing the simulation resolutions while keeping terrain data source constant (Figure 5a to Figure 5c), and the influence of terrain data source in the representation of the channel’s geometry and the floodplain landforms (Figure 5c,e).

Although reducing the simulation resolution from 2.5 to 30 m reduces the overall model performance and the ability to identify the TSFs exposed to floods, the computation times are reduced by more than 99%. On the other hand, even at moderate terrain resolutions (>5 m), the proposed methodology can identify more than 70% of the exposed TSFs relative to the benchmark results (see Figure 4a). Moreover, Table 5a shows there is no difference between the TSFs prioritized by simulations S-01 and S-03 (2.5 and 5.0 m resolution, respectively). The trade-off between accuracy and computation time suggests that, for assessments done over large spatial scales, using moderate resolutions may be appropriate for a screening-level prioritization.

The results revealed the potential for spurious results associated with high flow velocities and large grid sizes in steep terrain areas. For example, at 12.5 m resolution (S-06 and S-07), the TSF 29-IN was identified in the top 5 in terms of its FEI value of approximately 6.5 m² s⁻¹. However, the high values of FEI for this TSF cannot be attributed to the overflow of the Copiapó River since this deposit is located more than 25 m above
the riverbed. Moreover, the FEI value for 29-IN is unlikely to be associated with high runoff accumulation values since this TSF is draining an area smaller than 1 km². Therefore, the FEI value obtained using S-06 and S-07 suggests a numerical error due to a combination of high flow velocity and large grid size. This may be related to assumptions in the Shallow Water Equations that do not hold for steep slopes (Denlinger & O’Connell, 2008; Ni et al., 2019). Interestingly, 29-IN is no longer prioritised in the top 5 by simulation S-08 (30 m grid size), implying that this grid size smooths out the slope sufficiently enough to reduce this error. These errors in prioritisation suggest the need for high-quality terrain data to reduce local errors in slopes, in addition to expert review of results to filter out anomalous exposures.

### 4.2 Influence of channel and terrain features

The performance metrics of simulations S-03 and S-04 (see Table 4), show that the inclusion of terrain features such as buildings gives a slightly improved flood extent

#### Table 5

TSF prioritization according to flood exposure index (FEI) for different model configurations and inputs: A: Simulation resolution (model grid size), B: Inclusion of terrain and channel features, C: DEM quality and resolution, D: inclusion of rainfall-on-grid

| A. Simulation resolution | Top 5 | TSF ID | FEI (m²/s) | TSF ID | FEI (m²/s) | TSF ID | FEI (m²/s) | TSF-ID | FEI (m²/s) |
|-------------------------|------|--------|------------|--------|------------|--------|------------|--------|------------|
| S-01                    | 1    | 1-AB   | 12.06      | 1-AB   | 11.50      | 29-IN  | 6.50       | 1-AB   | 5.40       |
|                         | 2    | 36-IN  | 5.99       | 36-IN  | 3.73       | 1-AB   | 6.13       | 59-IN  | 4.75       |
|                         | 3    | 16-AC  | 2.85       | 16-AC  | 3.16       | 59-IN  | 4.59       | 16-AC  | 4.66       |
|                         | 4    | 59-IN  | 2.30       | 59-IN  | 2.96       | 16-AC  | 4.13       | 60-IN  | 3.56       |
|                         | 5    | 24-IN  | 2.16       | 24-IN  | 2.26       | 36-IN  | 3.07       | 24-IN  | 2.62       |

S-01 = 2.5 m; S-03 = 5.0 m; S-06 = 12.5 m; and S-08 = 30 m

| B. Terrain/ channel features | S-02 | S-03 | S-04 | S-05 |
|------------------------------|------|------|------|------|
| 1                            | 1-AB | 1-AB | 1-AB | 6.66 |
| 2                            | 16-AC| 3.16 | 36-IN| 3.73 |
| 3                            | 36-IN| 3.14 | 16-AC| 3.16 |
| 4                            | 59-IN| 2.65 | 59-IN| 2.97 |
| 5                            | 24-IN| 2.16 | 24-IN| 1.95 |

S-02 = bridges cleared, and no buildings raised; S-03 = bridges blocked, and buildings raised 3.5 m; S-04 = Bridges cleared, and buildings raised 3.5 m; and S-05 = bridges blocked, and no buildings raised.

| C. Terrain data source | S-07 | S-10 | S-12 | S-13 |
|------------------------|------|------|------|------|
| 1                      | 29-IN| 6.48 | 59-IN| 2.28 |
| 2                      | 1-AB | 6.13 | 1-AB | 1.26 |
| 3                      | 59-IN| 4.90 | 16-AC| 0.98 |
| 4                      | 16-AC| 4.12 | 60-IN| 0.89 |
| 5                      | 36-IN| 3.07 | 24-IN| 0.65 |

S-07 = 12.5-meter resolution DTM mosaic; S-10 = ALOS-PALSAR DEM 12.5m resolution, S-12= ALOS-PALSAR DEM 12.5m resolution with rivers burned; and S-13= SRTMGL1 DEM 30.0m resolution.

| D. Rainfall inclusion | S-02 | S-09 | S-10 | S-11 |
|-----------------------|------|------|------|------|
| 1                     | 1-AB | 11.50| 1-AB | 11.50|
| 2                     | 16-AC| 3.16 | 36-IN| 3.14 |
| 3                     | 36-IN| 3.14 | 59-IN| 2.65 |
| 4                     | 59-IN| 2.65 | 24-IN| 2.16 |
| 5                     | 24-IN| 2.16 | 60-IN| 0.79 |

S-02 = high resolution DEM with rainfall included; S-09 = high resolution DEM without rainfall; S-10 = moderate resolution DEM with rainfall included; and S-11 = moderate resolution DEM without rainfall.
as shown by a small increase of CSI and a small reduction of FAR. Additionally, the inclusion of these terrain features slightly reduced the RMSE. However, the improvements in terrain representation have no impact on computation times (see Figure 4b) and no impact on the number of TSFs identified as exposed, although the FEI magnitudes vary slightly. Moreover, neither the inclusion of terrain features nor of channel features had any noticeable effect on the prioritisation rankings presented in Table 5b. This suggests that the inclusion of flow obstacles such as bridges blocked by debris and buildings has little if no effect on the areas where most of the TSFs sit (see Figure 4b).

In this case, the inclusion of terrain features did not contribute to a better understanding of TSF flood exposure in Copiapo City and its surroundings. However, there are other potential cases in Chile (e.g., Andacollo town, Leiva et al., 2013) and worldwide (e.g., South Africa, Naicker et al., 2003), where terrain features typical of urban environments may play an important role in the evaluation of flood exposure of TSFs. These terrain features vary substantially across different historical mining regions and therefore it is difficult to extrapolate any conclusions regarding its inclusion to other potential case studies.

4.3 Influence of input terrain data

Based on the performance metrics of simulations S-10 and S-13 (see Table 5c), it can be observed that the RMSE values increase by 0.91 m when using the ALOS PALSAR RTC DEM (S-10) and 1.2 m when using SRTMGL1 (S-13). Additionally, simulations S-10 and S-13 have higher FAR values and lower CSI suggesting the use of satellite derived terrain data hinders the ability of SWIFT to accurately predict the flood extent. Finally, to test if this reduction in performance was caused by poor representation of the channel topography of Copiapo River and Q. Paipote, these two river channels were incorporated by carving 1.5 m into the ALOS PALSAR RTC (S-12) in a process commonly known as “river-burning.” However, this did not improve upon the FEI values obtained for S-10 (Figure 4c) or the flood extent performance metrics.
(Table 5). This suggests that the additional effort of river-burning is not worth it for this application. It is important to notice that the “river-burning” process was not necessary in the case of the high-resolution DTM, since this terrain data source already captures the channel topography, and it differentiates the channels of Copiapó River and Q. Paipote form the surrounding floodplain (see Figure 5a,c).

On the other hand, the results obtained with the SRTMGL1 product (S-13) and ALOS PALSAR RTC (S-10) were comparable in terms of average FEI values and percentage of TSFs identified as exposed relative to the benchmark simulation (see Figure 4c). Although the number of TSFs identified as exposed by S-10 and S-12 is lower when compared with S-07 (surveyed high-resolution DTM), approximately 70% of these TSFs were also identified as exposed by the benchmark. Moreover, the prioritisation of TSFs in terms of FEI does not change significantly regardless of the DEM source (Table 5c). This supports the view that moderate resolution DEMs can be considered an alternative to high-resolution DTMs for a first-stage prioritisation of TSFs over large spatial scales.

Finally, it is worth mentioning that previous studies have shown that the lack of high-resolution terrain data (DTM) hinders the ability of hydrodynamic models to produce realistic flood outputs (Hsu et al., 2016; Saksena & Merwade, 2015). Furthermore, the SRTMGL1 elevation product is known to have low vertical accuracy and terrain sinks caused by radar shadows as described by Sanders (2007). This suggests that the reduction in SWIFT’s performance obtained with S-13 and potentially also S-10 can be attributed to the quality of available input data rather than the model’s structure or the model capabilities.

### 4.4 Influence of rainfall-on-grid

Rainfall-on-grid was useful to determine locations where water can pool due to the presence of natural sinks or manmade terrain depressions (e.g., excavations for road construction, foundations, mining, etc.). The inclusion of rainfall-on-grid without infiltration offers a hypothetical representation of the extreme scenario that all of the rainfall becomes runoff. Due to the low rainfall rates compared with possible infiltration capacities, most of the peri-urban areas modelled as flooded due to accumulation of runoff are unlikely to have been flooded after the flood event of March 2015. Infiltration experiments in these areas, or observations of local flooding in these areas during the event, would allow a more detailed exploration of exposures to pluvial flooding. However, with the available results, it can be concluded from Figure 4d that up to 88% of all the TSFs identified as exposed by S-02 and 94% for S-10 are potentially exposed to locally generated runoff under extreme local rainfall intensities. Additionally, Figure 4d along with Figure A4 allowed us to conclude that only TSFs 1-AB, 26-IN, 39-IN and 59-IN are modelled to be endangered directly by the fluvial dynamics of Copiapó River.

When analysing the flood extent pattern of simulations S-10 and S-11 (see Figure A4), it can be observed that rainfall-on-grid generates accumulation of surface runoff at two different locations parallel to main roads leaving Copiapó city in a south–north direction. However, the vertical resolution of the DEMs does not allow us to conclude if the creation of these runoff accumulation zones can be attributed to the hydro-filling process applied to the moderate resolution DEMs prior to running the flood inundation model or due to the alteration of the natural terrain profile due to the construction of the roads. This suggests that in the event of locally runoff generation, the quality of the DEM or DTM used to evaluate rainfall-on-grid can play an important role in the interpretation of flood exposure results. Furthermore, it is important to acknowledge that incorporating infiltration losses in 2D flood models of arid regions such as Copiapó city and its periphery, can reduce the magnitudes of flood heights considerably. This highlights the need to investigate infiltration rates for the arid soils of the Atacama Desert, which would allow for a more precise evaluation of the impacts of rainfall-on-grid and flood modelling results and the impacts on the flood exposure of tailings deposits in northern Chile.

#### 4.5 Prioritisation of TSFs

The characteristics of the prioritised TSFs point to the need for management of environmental risk. All five of the TSFs prioritised by S-03 (1-AB, 16-AC, 24-IN, 36-IN and 59-IN) were constructed using the coarse fraction of tailings as part of the embankments (“Tranques” according to the Chilean terminology). This is important from the potential pollution and erosion perspective because tailings’ chemical and physical instability can be considered higher than common dam construction materials such as clay (Roche et al., 2017). Considering that tailings’ particle size distributions typically range between 0.001 and 0.3 mm, depending on the type of commodity being exploited and the technology used for mineral processing (Kossoff et al., 2014; Vallero & Blicht, 2019; Williams, 2016), the magnitudes of FEI presented in Table 5 are potentially high enough to erode flooded tailings particles (Geremew & Yanful, 2010; Yanful & Catalan, 2002). Additionally, all the TSFs prioritised by S-03 (except for 1-AB), are located upstream...
of locations where sediments samples have been found to contain concentrations of Hg, Pb and Al that can pose a significant environmental risk (Izquierdo et al., 2020). Moreover, Izquierdo et al. (2020) reported concentrations of As, Ba, Cr, Cu, Fe, Mn and Ni downstream of some of these prioritised TSFs that exceed guideline thresholds (USEPA, 2015). Moreover, TSFs 39-IN, 59-IN and 70-IN were also prioritised based on the pollution potential analysis made by Soublette et al. (2011). The only TSF out of the five prioritised here that has not been prioritised by previous studies focusing on mine waste pollution was 1-AB, which was consistently prioritised in terms of FEI by all the evaluated simulations. This TSF corresponds to an abandoned pile of copper tailings, and it is located downstream of Universidad de Atacama campus on the left bank of Copiapó River (for more details see Table A1). An obvious extension of this study, towards a fuller risk assessment, would be to combine the FEI results with pollution generation potential as guided by these studies.

5 | CONCLUSIONS

This study used Copiapó River Basin as a case study to demonstrate the usefulness of a 2D hydrodynamic model, SWIFT, for assessing flood exposure of old and abandoned tailings storage facilities (TSFs) in northern Chile. The results suggest that at least eight TSFs can be considered exposed to flood flows and vulnerable to erosion from a flood event with an estimated return period of 50 years, such as the one occurred in March 2015. Sensitivity of results to terrain data source, model grid size, inclusion of rainfall-on-grid and treatment of flow obstacles such as buildings and bridges blocked was tested with the objective of understanding trade-offs between accuracy of results and required modelling complexity and resources. This showed that, despite accuracy losses, acceptable prioritisation of TSFs could be achieved using moderate resolution models with freely available DEMs. Results also showed that if rainfall-on-grid exceeds the soil infiltration capacity, locally generated runoff has the potential to reach many TSFs in the case study area. As there is not enough data available to calibrate an infiltration model in the case study region, this hypothesis must be validated with further research. On the other hand, as little is known about the geochemistry, solubility and bioaccessibility of potential pollutants contained in the prioritised TSFs, and the downstream transport and receptors of any released contaminants are also uncertain, it is impossible to establish the level of risk that these TSFs pose. Therefore, it is recommended to integrate this modelling result into a more comprehensive risk assessment that finalises priorities for TSP management.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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### A.1 List of TSFs inside modelling extent

**Table A1** Summary of TSFs 'within the study area and flood exposure results based on benchmark simulation (S-03)

| ID | E coordinates (m) | N coordinates (m) | Embankment type | Commodity        | Approved volume (m³) | Mine                      | Owner/company                           | Flood proximity index (FPI) | Flood hazard S-03 (m² s⁻¹) |
|----|------------------|------------------|-----------------|------------------|----------------------|--------------------------|----------------------------------------|------------------------------|------------------------------|
| 1-AB | 366094.3149     | 6973468.441      | Tranque         | Copper           | 8000.00              | planta la chimba         | unknown                                | 1                            | 11.5                         |
| 2-AB | 365965.3114     | 6973628.093      | Tranque         | Gold-Copper      | 71000.00             | planta guggiana         | domingo guggiana                      | 0                            | 0                            |
| 3-AB | 366636.6906     | 6968489.315      | Tranque         | Copper           | 175000.00            | planta la union (ex san | minera union                           | 0.33                         | 0.001                        |
| 4-AC | 366317.9093     | 6968009.99       | Dam             | Copper           | 280495.00            | planta irmita           | acibol spa                             | 0                            | 0                            |
| 5-AC | 369586.8995     | 6966696.689      | Tranque         | Copper           | 242424.00            | planta vititita azul    | soc. contractual minera alianza       | 1                            | 0.1                          |
| 6-AC | 366008.738      | 6967647.389      | Dam             | Copper-Gold      | 72000.00             | planta arcardio         | soc. guerero hermanos y cia. ltda.    | 1                            | 0.003                        |
| 7-AC | 367809.3314     | 6969553.876      | Tranque         | Copper           | 26000.00             | planta corona           | soc. minera candelaria                | 1                            | 0.17                         |
| 8-AC | 367410.879      | 6969790.986      | Dam             | Copper           | 26000.00             | planta puerto rico      | soc. minera fortuna ltda              | 0.33                         | 0.001                        |
| 9-AC | 365937.7149     | 6967627.744      | Dam             | Copper           | 17560.00             | planta el cateador      | sotratec-minart ltda                  | 0.33                         | 0.003                        |
| 10-AC| 374360.2355     | 6964413.285      | Tranque         | HIERRO           | 14200000            | planta maria isabel     | zsc minerals                           | 0                            | 0                            |
| 11-AC| 367832.763      | 6969503.273      | Tranque         | Gold             | 65240.00             | planta day              | miguel day                             | 0                            | 0                            |
| 12-AC| 365944.0724     | 6966925.994      | Dam             | Copper           | 2400.00              | planta san eduardo      | minex s.a.                             | 0.33                         | 0.001                        |
| 13-AC| 366294.3935     | 6967508.8        | Dam             | Gold             | 4380.00              | planta ojos de agua     | natiman flores diaz                   | 0.33                         | 0.138                        |
| 14-AC| 369869.6054     | 6965601.333      | Tranque         | Copper           | 31200.00             | planta santa laura      | nelson zuriga carvajal                 | 1                            | 0.297                        |
| 15-AC| 367309.419      | 6969385.409      | Dam             | Gold             | 37461.00             | planta rapelina         | pedro jesus castillo vega              | 0                            | 0                            |
| 16-AC| 374840.4798     | 6971182.011      | Tranque         | Copper           | 14200000.00         | kozan                    | scm atacama kozan                     | 1                            | 3.161                        |
| 17-AC| 369079.958      | 696704.098       | Tranque         | Copper-Gold      | 72490.00             | planta vititita azul    | soc. contractual minera alianza       | 1                            | 0.268                        |
| 18-IN| 366000.7562     | 6967761.398      | Dam             | Gold-Copper      | 36000.00             | planta alemana          | ana maria munizaga                    | 1                            | 0.261                        |
| 19-IN| 365267.928      | 6967265.977      | Tranque         | Gold             | -                    | amanda                  | cia. Minera oro verde                  | 0                            | 0                            |
| 20-IN| 370095.0906     | 6966543.693      | Dam             | Gold             | 8308.00              | planta purificacion     | cia. Minera purificacion               | 0                            | 0                            |
| 21-IN| 369988.1987     | 6966544.751      | Tranque         | Gold             | 500                  | planta purificacion     | cia. Minera purificacion               | 0.66                         | 0.279                        |
| 22-IN| 369991.5061     | 6966591.053      | Tranque         | Gold             | 12,000               | planta purificacion     | cia. Minera purificacion               | 1                            | 0.279                        |
| 23-IN| 369993.2258     | 6966638.943      | Tranque         | Gold             | 600                  | planta purificacion     | cia. Minera purificacion               | 0.66                         | 0.287                        |
| 24-IN| 370138.7395     | 6968987.587      | Tranque         | Copper           | 245,160              | planta san esteban      | cia. Minera san esteban                | 0.33                         | 2.26                         |
| 25-IN| 366407.2893     | 6967943.299      | Dam             | Copper-Gold      | -                    | luz elena               | carlos irabaren                       | 0.33                         | 0.181                        |
| 26-IN| 370234.7834     | 6969133.637      | Tranque         | Copper           | 67,200               | planta san esteban      | cia. Minera san esteban                | 0.66                         | 0.41                         |
| 27-IN| 370187.1583     | 6969053.468      | Tranque         | Copper           | 48,000               | planta san esteban      | cia. Minera san esteban                | 0                            | 0                            |
| 28-IN| 369370.3621     | 6968250.855      | Tranque         | Copper           | 279771.00            | planta santa esteban (ex | cia. Minera san esteban primera        | 1                            | 0.291                        |
| 29-IN| 369432.2747     | 6967960.342      | Tranque         | Copper           | 1508240.00           | planta santa esteban (ex | cia. Minera san esteban primera        | 1                            | 0.178                        |
| 30-IN| 369595.7875     | 6968177.83       | Tranque         | Copper           | 301886.00            | planta santa esteban (ex | cia. Minera san esteban primera        | 0                            | 0                            |
| 31-IN| 367225.246      | 6969446.037      | Tranque         | Copper           | 27,300               | planta san patricio     | cia. Minera san patricio               | 0                            | 0                            |
| 32-IN| 366464.6591     | 6972231.243      | Tranque         | Copper           | 1,602,066            | ojancos                 | cmc sali hochschild s.a.               | 1                            | 0.1142                       |
| 33-IN| 365002.7657     | 6973741.225      | Tranque         | Copper-Gold      | 3115875.00           | bodega alto             | cmc sali hochschild s.a.               | 1                            | 0.049                        |
| 34-IN| 366892.2286     | 6972040.742      | Tranque         | Copper           | 3202671.00           | ojancos                 | cmc sali hochschild s.a.               | 1                            | 0.243                        |
| 35-IN| 366485.6001     | 6967929.541      | Dam             | Copper-Gold      | 5200.00              | luz elena               | carlos irabaren                       | 1                            | 0.146                        |

(Continues)
| ID  | E coordinates (m) | N coordinates (m) | Embankment type | Commodity | Approved volume (m³) | Mine | Owner/company | Flood proximity index (FPI) | Flood hazard S-01 (m² s⁻¹) |
|-----|------------------|------------------|----------------|-----------|---------------------|------|---------------|----------------------------|----------------------------|
| 36-IN | 367133.5271 | 6972269.343 | Tranque | Copper | 1800.00 | ojancos |cmc sali hochschild s.a. | 0.66 | 3.73 |
| 37-IN | 364521.2231 | 6973769.006 | Tranque | Copper-Gold | 515600.00 | bodega alto |cmc sali hochschild s.a. | 1 | 0.204 |
| 38-IN | 372382.6144 | 6970938.957 | Dam | Gold-Copper | 5732.00 | planta andra | comercial ledesma representaciones | 1 | 0.071 |
| 39-IN | 370877.3038 | 6968041.71 | Tranque | Copper-Gold | 4300.00 | planta tania | delia nieto robe | 1 | 0.46 |
| 40-IN | 370160.5751 | 6966612.485 | Tranque | Gold | 2760.00 | unknown | unknown | 0 | 0 |
| 41-IN | 370253.1795 | 696808.277 | Tranque | Gold | 4276.00 | unknown | unknown | 0 | 0 |
| 42-IN | 370327.9244 | 696846.688 | Tranque | Gold | 8442.00 | unknown | unknown | 0 | 0 |
| 43-IN | 36913.7021 | 697091.417 | Tranque | Gold | 4050.00 | planta santa teresa | elias resk contreras (soc. minera santa teresa) | 0 | 0 |
| 44-IN | 366918.9647 | 6968912.655 | Tranque | Gold | 28200.00 | planta santa teresa | elias resk contreras (soc. minera santa teresa) | 0 | 0 |
| 45-IN | 367011.5981 | 6968943.875 | Tranque | Gold | 2800.00 | planta santa teresa | elias resk contreras (soc. minera santa teresa) | 0 | 0 |
| 46-IN | 368496.3292 | 6969648.76 | Tranque | Copper | 15200.00 | planta porvenir | carlos soto fuentesalba | 0 | 0 |
| 47-IN | 366948.0981 | 696822.18 | Tranque | Gold | 32650.00 | planta santa teresa | elias resk contreras (soc. minera santa teresa) | 0 | 0 |
| 48-IN | 370298.5741 | 695454.046 | Dam | Gold | 4785.00 | santa rosa | exequiel bugueno | 0.66 | 0.224 |
| 49-IN | 370264.6488 | 695442.4 | Dam | Gold | 15772.00 | santa rosa | exequiel bugueno | 1 | 0.048 |
| 50-IN | 370845.7128 | 6970052.556 | Tranque | Gold | 20000.00 | planta castellon | hector castellon | 1 | 0.033 |
| 51-IN | 370742.894 | 6971970.847 | Tranque | Copper | 10637.00 | planta cuesta cardones | manuel achu perez | 0.66 | 0.001 |
| 52-IN | 37829.7463 | 696981.087 | Tranque | Copper-Gold | 5600 | planta cuesta cardones | manuel achu perez | 0.66 | 0.001 |
| 53-IN | 368457.1708 | 696949.301 | Tranque | Copper | - | planta porvenir | carlos soto fuentesalba | 0 | 0 |
| 54-IN | 367197.2354 | 6969252.059 | Tranque | Copper-Gold | 17600 | planta day | miguel day | 0 | 0 |
| 55-IN | 367479.811 | 696942.988 | Tranque | Gold | 17600 | planta day | miguel day | 0 | 0 |
| 56-IN | 366277.5109 | 697856.383 | Tranque | Gold-Copper | 20782.00 | auricop | minera san marino | 0 | 0 |
| 57-IN | 369579.975 | 696948.219 | Dam | Copper | 4062 | planta san eduardo | minex s.a. | 0.33 | 0.001 |
| 58-IN | 366311.3269 | 6967537.009 | Dam | Gold | 16667 | planta ojos de agua | natiman flores diaz | 1 | 0.138 |
| 59-IN | 370695.667 | 6968110.16 | Tranque | Gold-Copper | 33814.00 | planta ilaucaven | nutex hnos | 1 | 2.96 |
| 60-IN | 370621.5835 | 696828.054 | Tranque | Gold-Copper | 210795 | planta ilaucaven | nutex hnos | 0.66 | 1.203 |
| 61-IN | 366905.9295 | 6967802.404 | Tranque | Copper-Gold-Iron | 187300 | planta op (ex farah) | op mining chile spa | 1 | 0.015 |
| 62-IN | 367134.53 | 696813.404 | Dam | Copper-Gold | 108000 | planta op (ex farah) | op mining chile spa | 0 | 0 |
| 63-IN | 365659.854 | 696725.055 | Tranque | Gold | 66667 | planta monserrat | oscar gomez escober | 0.66 | 0.001 |
| 64-IN | 372402.5857 | 697099.228 | Dam | Gold-Copper | 6404.00 | planta andra | scm san sebastian | 0 | 0 |
| 65-IN | 369994.2552 | 695751.208 | Dam | Copper | 3984.00 | planta candelaria | sdm escondida una de las sierras rajo de oro | 1 | 0.224 |
| 66-IN | 370007.4844 | 696585.273 | Dam | Copper | 10578.00 | planta candelaria | sdm escondida una de las sierras rajo de oro | 0 | 0 |
| 67-IN | 369932.6072 | 6965867.937 | Dam | Copper | 1218.00 | planta candelaria | sdm escondida una de las sierras rajo de oro | 0 | 0 |
| 68-IN | 37945.7386 | 6966782.777 | Tranque | Gold | 4800 | planta vititax azul | soc. contractual minera alianza | 0 | 0 |
| 69-IN | 37241.5453 | 696960.444 | Tranque | Copper | 46800 | planta puerto rico | soc. minera fortuna ltda. | 1 | 0.156 |
| 70-IN | 374342.8884 | 698381.665 | Tranque | Copper-Gold | 13000 | planta san joaquin | soc. minera san joaquin | 0.33 | 0.43 |
| 71-IN | 374230.1674 | 698384.115 | Tranque | Copper-Gold | 8500 | planta san joaquin | soc. minera san joaquin | 0 | 0 |
| 72-IN | 374296.3133 | 698385.353 | Tranque | Copper-Gold | 13700 | planta san joaquin | soc. minera san joaquin | 0 | 0 |
| 73-IN | 366021.3234 | 697554.719 | Tranque | Copper | 35120 | planta el capeador | sotratec-minart ltda. | 0.33 | 0.003 |
| 74-IN | 375136.7009 | 695731.075 | Tranque | Gold | 2500 | planta la florida | victor jensen | 1 | 0.106 |
| 75-IN | 375090.3988 | 695684.773 | Tranque | Gold | 3000 | planta la florida | victor jensen | 1 | 0.2 |

Note: TSFs’ information provided by the Chilean Service of Geology and Mining (SERNAGEOMIN, 2020).
A.2  |  Flood exposure intercomparison

FIGURE A1  Influence of simulation resolution on TSF's flood exposure. Flood hazard values correspond to simulation results for flood event occurred at Copiapó River basin between 26 and 28 March 2015.
Figure A2  Influence of channel and terrain features on TSIF’s flood exposure. Flood hazard values correspond to simulation results for flood event occurred at Copiapó River basin on 26 and 28 March 2015.
FIGURE A3  Influence of terrain data quality on TSF’s flood exposure. Flood hazard values correspond to simulation results for flood event occurred at Copiapó River basin on between 26 and 28 2015.
FIGURE A4  Influence of rainfall inclusion on TSF’s flood exposure. Flood hazard values correspond to simulation results for flood event occurred at Copiapó River basin on 26–28 March 2015.