Twenty-Five Years of Evolution of Integrated Water Management and Integrated Water Balance Modelling at Mine Sites

Lloyd R. Townley[1,2]

[1]GW-SW Pty Ltd, Dee Why NSW 2099, Australia, lloyd@gw-sw.com, ORCID 000-0003-2923-628X

[2]School of Environmental Science and Engineering, Nanjing Tech University, Nanjing, China

Abstract

Mine sites throughout the world are similar but different. They have different topography, climate, geology, target minerals, mining methods and processing methods, but mining and processing are always affected by water, and water in the environment is always affected by mining and processing on site. At every stage in the project pipeline, from Conceptual to Order of Magnitude Study (OoM) to Pre-Feasibility Study (PFS), from Feasibility Study (FS) to Engineering, Procurement and Construction Management (EPCM), from commissioning to operations, and then to expansion and closure studies, there are reasons to consider water management holistically, in an integrated way, to ensure success in operations and to mitigate risks. Simulation modelling can be used to support decisions during design and operations, and with 25 years of evolution of integrated water balance modelling, there are now clear patterns that show when integrated balance modelling is especially useful.

Keywords: Integrated water management, water balance modelling, mining

Introduction

To understand the concept and importance of integrated water balance modelling, it is first necessary to understand the concept of integrated water management. In essence this means consideration of all issues related to water management on a mine site in an integrated way, simultaneously or at least in sequence, to avoid the pitfalls of independent management of different issues in different silos within a site management team. This is harder than it sounds. The issues and the silos appear very early in the mining life cycle (cf. the project pipeline), and persist in similar and different forms during operations, unless specific efforts are made to ensure communication between these silos.

Focusing now on water balance modelling, there are several distinct times during the mining life cycle when integrated models are useful, and each requires a special kind of modelling. These times include: (1) during conceptual, OoM and PFS studies, when it is useful to understand water supply demands throughout the Life of Mine, in areas with intermittent rainfall and/or insufficient storage, and requirements for mine pit dewatering, e.g. in high rainfall environments where it may be difficult to store excess water that cannot be discharged; (2) after a mine has been commissioned, when an operational model predicting 12-24 months ahead can help mine managers to understand the risks associated with failing to build additional water management infrastructure; (3) when there is risk of poor quality water being released, and it is necessary to predict potential environmental impacts downstream, beyond mining lease boundaries, including the effects of dilution, adsorption and reactive transport in porous media, drains and streams; and (4) during expansion studies and closure planning, combining some aspects of each of these three types of models.

Which teams manage water?

It takes time to understand who has responsibility for water management on mine sites, and how and when problems may arise. How water is managed also depends on the owner of the project or mine:

- startup or junior mining companies (the "juniors", without any operations or perhaps with one) tend to run on shoestring budgets and rely on consultants for services, with specific services provided by different types of consultants, and sometimes with less, sometimes with more, communication between teams;
- mid-tier mining companies (the "mid-tiers", with a handful of operating mines (say 3-5) and a number of projects in the pipeline) usually use consultants, because they are not yet large enough to have technical specialists in-house, but some try to bridge the gap, operating more like a small major; and
- major mining companies (the "majors", with tens of operating mines and many projects in the pipeline) tend to have in-house technical expertise to oversee operations and to guide studies for projects, even if specialist consultants are also sometimes used.

During the **studies phase** (conceptual, OoM, PFS and FS studies, and sometimes during expansion studies), a mining company often contracts a large international consulting firm to manage the overall study. These firms often have specific in-house skills in one or more areas, for example in extractive metallurgy, process design and EPCM for all the civil, mechanical, electrical and other engineering required to build a process plant and all associated mine infrastructure; these firms sometimes have in-house expertise in geology and mine design, but they usually subcontract smaller companies to provide geotechnical advice (e.g. to recommend pit wall slope angles), to design tailings storage facilities (TSFs) and to provide hydrogeological advice (related to design of water supply borefields and/or active or passive mine dewatering) and hydraulic design (for diversion channels, dams, pipelines and pumps). The large consulting firms also usually contract a separate large consulting company to prepare an Environmental and Social Impact Assessment (ESIA, in modern parlance), and the latter subcontracts others to undertake baseline hydrological studies and to assess potential impacts of the proposed project on surface water, groundwater and the ecosystem. The use of so many specialised teams sometimes leads to a lack of integration.

Many teams make assumptions about the movement of water and make calculations, often relatively independently:

- process engineers nearly always assume steady flow, with water demand driven by the assumed percent solids in tailings, and they then estimate steady raw water makeup demand based on assumptions about tailings decant;
- tailings engineers collate climatic data and make many assumptions about water balance (including consolidation, beaching angles and return of decant to a process water pond), as well as leakage to underdrains, toe drains or the soil beneath the floor of a TSF (unlined or lined); they rarely assess environmental impacts;
- geochemists are engaged to recommend the placement of potentially acid forming (PAF) waste in Waste Rock Dumps (WRDs), and the management and possible treatment of acid rock drainage (ARD);
- geotechnical engineers often focus on the near field of pit walls and underground workings;
- civil/water engineers collate climatic data and design drainage systems and floodways and do not usually assess potential environmental impacts;
- hydrogeologists design water supply borefields and estimate mine pit inflows and potential environmental impacts; and
- environmental consultants also collate climatic data and assess environmental impacts.

It requires focus to complete all of these scopes of work in an efficient manner, with different teams making consistent assumptions. Integration is often difficult to achieve.

During **operations**, each mine has a mine manager, who is usually a mining engineer or a process engineer by training, depending on what is most critical on an individual mine site, and on rare occasions a geologist or environmental specialist. The mine manager is supported by a management team: a geology or geoscience manager, a mining manager, a processing manager, an infrastructure manager, an environmental (Environment, Health and Safety or EHS) manager, and perhaps another. Because an Environmental and Social Management Plan (ESMP) often includes an Environmental Management System (EMS) consistent with the ISO 14001 series of Standards, it is common for operations to commence with a Surface Water Management Plan (SWMP, or Surface Water Management and Monitoring Plan, SWMMP) in place, and perhaps a Groundwater Management Plan (GWMP or similar). These plans are written to help operations to comply with requirements (legislation, regulations and licence conditions) that are focused on environmental management, but they are not usually focused on operational water management issues and practices that are required within an operation to meet operational requirements. Water is always the "poor cousin" relative to the most important disciplines of mining and processing. There is almost never a "water manager" on site, although some majors understand the desirability of such a role, a "water czar", not a line management role, but a person (reporting to the mine manager) whose role is to oversee a less formal "water team" and to encourage if not ensure integrated water management. Often there is an assumption that water management should be the responsibility of the EHS manager, simply because WMPs include the word "water", and even though such plans may have been written by city-based consultants who have never been to site. Effective integration is always difficult.

Special challenges in mine water management

Why is integrated modeling at mine sites different or especially challenging? One could argue, correctly, that software for simulating the movement of surface water (hydrology, hydraulics and hydrodynamics) and groundwater in natural systems has evolved significantly in the past 20–30–40 years, and software for simulating movement of water in engineered systems (pipe networks, pumps, water treatment etc.) is also mature; there are many commercial and open-source software packages available in all these areas. However simulation of the movement of water on mine sites remains difficult largely because the geometry, features and properties of mine sites change every day, and at monthly and annual intervals they change noticeably. Some technical software allows for changes in geometry, but no software package can handle all aspects of water management on a mine site, including continuously changing geometry, or certainly not without unreasonable effort required to represent the dynamic changes of geometry. This is a major reason why different approaches have evolved and why software for mine site water management needs to be extensible.

So far we suggest the possible need for integrated water balance modelling. In fact we sometimes need integrated balances of water, mass and solutes. A mine schedule defines the sequence in which individual blocks in a 3D mine geological model are removed from the mine, whether open cut or underground. Each block includes volume and mass of mineralised ore that is sent to Run-of-Mine (ROM) pads or a processing plant and waste rock that is directed to WRDs; the rock in both cases contains some water that was not released in the drilling and blasting or other mining process. In many types of mining, ore that is crushed and milled ultimately reports to a TSF; in other types of mining, such as bauxite or nickel laterites, the ore is completely dissolved and precipitates as a residue, hence Residue Storage Facilities (RSFs) rather than TSFs. WRDs and TSFs/RSFs are constructed landforms that grow within expanding footprints throughout the Life of Mine. Management of water that falls on and within these landforms is important, to reduce the mobilisation and transport of solutes. Integrated mass balance modelling can help us to estimate or predict dynamic changes in catchment areas which are important for water balances.

Solutes of importance include tailings liquor, which can have concentrations as high as 50,000-100,000 mg/L. Such liquor is more dense than seawater and certainly more dense than groundwater below the land surface. Density becomes important when leakage reaches the water table, because dense groundwater often leads to dense plumes that can propagate in unexpected directions, following the topography of low hydraulic conductivity layers beneath the surface rather than surface topography. Acid rock drainage (ARD) can be produced within and discharged from mines or can be generated within WRDs and occasionally TSFs. Sometimes it is important and useful to compute solute balances in conjunction with water and mass balances, although estimation of source concentrations is challenging.

Evolution of balance modelling methods

Thirty years ago, in 1995, while simple balance modelling was possible using Lotus 1-2-3/W Release 5 (16-bit) and Microsoft Excel 95 (v7.0) (32-bit) for the Microsoft Windows 3.1x operating system, it was still quite common to write applications for specific purposes using languages such as Fortran. Barr and Townley (1991ab) developed a water and solute balance model for many coupled ponds, for application to solar salt production for the Shark Bay Salt Joint Venture in Western Australia, a special type of "mining" that is relevant because of the challenges of simulating many coupled storages. Perhaps this is the first important concept in integrated modelling on mine sites, the need to store water in many storages (dams, ponds and/or tanks), with water flowing from one to another under gravity or being pumped back according to agreed operating rules, sometimes with overtopping that cannot be prevented (but a destination must be assigned) and sometimes drying out. Drying, due to an excess of outflows over inflows, with ever-present evaporation, is the hardest phenomenon to represent in software, because the time at which dryness is reached is nearly always part way through a computational time step.

Twenty-five years ago, the author developed a sitewide water and solute balance model for the Mt Gordon copper mine in Queensland, Australia, using XPSWMM, which was first released under the Microsoft Windows operating system in 1997. Professionals working on urban stormwater drainage have been using the US EPA's Storm Water Management Model (SWMM) since 1971. The XP (expert) graphical user interface made it relatively easy to create a node-link model of flows between storages on site, with catchments generating runoff, but SWMM was not designed to handle the complexities of mining, especially with time-varying catchment areas. As mentioned above, this is a second important concept in integrated modelling: the geometry of catchments on mine sites is nearly always time-varying. XPSWMM is now supported by Innovyze (2024).

In the late 1990s, the author experimented with the use of other simulation software, notably STELLA and ExtendSim, both of which were first released in the mid-1980s. ExtendSim is used in the mining sector today, although perhaps not widely with application to water management. In fact the field of simulation modelling is very diverse, and there are many specific types of modelling; a review by Roberts and Pegden (2017) provides useful insights.

In 1990, a team inside Golder Associates in Seattle started to develop a general simulation package called GoldSim (see www.goldsim.com/Web/Company/History and a blog referred to therein; the "gold" in the product name comes from the name of the company, not the metal). GoldSim was first released in 1999, and the author first used GoldSim in 2006, at a time when Rio Tinto was encouraging the development of sitewide balance models for operating mines to assess short-term operational water-related risks. In the past nearly 20 years, the author has developed more than ten models of mine sites, at different stages of development, and reviewed many more. The current release of GoldSim (GoldSim Technology Group 2025) is popular in the mining sector, used at hundreds of mine sites, indeed mining and water balance make up 50-60% of the current user base. GoldSim is a general purpose simulation framework, that can be thought of as a high-level programming language that allows users to simulate many kinds of systems in a flexible way. GoldSim differs from spreadsheets, system dynamics software and discrete event simulators, (see www.goldsim.com/Web/Products/GoldSim/Comparison) but combines some of the best features of each. GoldSim has powerful Monte Carlo capabilities, making it ideal for quantitative risk assessment (QRA). GoldSim can use Excel for input and output (as well as databases) and is highly extensible using dynamic linked libraries (DLLs) for communication with other software. GoldSim has been linked to MODFLOW, FEFLOW, PHREEQC and many more packages used in the mining sector. The GoldSim Model Library (online) contains hundreds of examples of applications, as well as examples of how to use each of the individual "elements" that are used to construct a model. GoldSim 15 introduces a new Controller element that will find widespread application in mine water management modelling, for representing transfers between ponds.

In 2006, the author was also introduced to OPSIM (see OPSIM Pty Ltd 2025) and had the opportunity to develop a model for one mine in Australia. OPSIM was obviously a product written by water engineers for water engineers, using the terminology and naming conventions of water engineers, and focused specifically on the mining sector. OPSIM at that time could be configured relatively easily, but was far less extensible than GoldSim, which is a high-level development environment. While the learning curve for OPSIM was arguably shorter, it was not as powerful. Things have clearly changed, because OPSIM has continued to evolve and now boasts capabilities that include movement of water, mass and solutes, as well as special modules for geochemistry, real-time integration with online information systems and a Water Accounting Framework (WAF) aligned with the Global Reporting Initiative (GRI). OPSIM continues to be used in the mining sector, often by teams within mining operations (John Macintosh, pers.comm.).

What are the benefits of modelling? How can integrated modelling help?

Models should be designed to meet specific objectives, to answer specific questions:

- Typical objectives during the studies phase relate to design of dams and ponds, i.e. how big do they need to be, and what should be their operating rules, in order (i) to ensure sufficient water supply through months and years of drought, or (ii) to contain contaminated water when heavy rain falling into open cut pits, or onto WRDs and TSFs, leads to large volumes of mine-affected water, or when discharge of groundwater into mines is very large? Corollaries include the questions of how big pipes and pumps need to be for mine pit dewatering or to move water between storages according to operating rules.
- Typical objectives during operations are similar, but by this time most infrastructure is already in place, so questions relate to potential additional infrastructure or changes in operating rules. Looking ahead through the next dry season or two, what is the risk that available storage will not be sufficient to meet makeup water and process water demands, and if the risk is too high, what changes in infrastructure and/or operating rules would mediate that risk? Looking ahead through the next wet season or two, what is the risk that failing to lift a TSF could result in overtopping, or if storage on the surface of a TSF is used for emergency water storage (not generally recommended), what is the risk that there is insufficient storage on site to contain contaminated water, so that mining must cease?

In both sets of examples, the focus of modelling is on design, based on QRA.

Guidelines for integrated water balance modelling at mine sites

The author is not aware of any industry-wide guidelines for integrated (water, mass and solute) modelling at mine sites, nor is he suggesting that such guidelines are needed. It is useful however to read guidelines of other kinds, and to consider what can be learned and applied.

The Australian Groundwater Modelling Guidelines (AGMG) (Barnett *et al.* 2012) were written by many authors, following workshops with stakeholders from government and many industry sectors. The guidelines were not universally accepted, indeed the need for guidelines was debated and rejected by some, but nevertheless the guidelines have been useful for some stakeholders. One key feature is that the guidelines were not written for modellers, who learn their trade in universities and in the workplace, after gaining experience developing many models; the guidelines were written primarily for the people who read reports on the results of modelling, to help them to understand what a model is, how it is developed and how it can be useful. In some ways this paper is written with similar intent: it is not intended to teach modellers how to develop models, but rather to provide context and to tell some of the stories that are not so often told.

A key recommendation in the AGMG is that a model must have clear objectives. A model should never be developed simply because someone believes a model might be useful. A model should aim to analyse/explain behaviour of a system in the past or to predict specific behaviour in the future, usually related to flows of water or mass or solutes. It should be designed to answer specific questions, often related to design of mine and water management infrastructure and choice of operating rules. Specific objectives are essential to allow a modeller to design a model to achieve those objectives. Sometimes it is difficult to add more objectives later, because meeting those new objectives would require a different modelling approach or a different model structure. It is therefore important to invest time and effort into setting objectives at the start.

The AGMG also recommend a staged approach. This is especially difficult during the studies phase, where the lead consulting firm may prefer a single deliverable rather than multiple stages and workshops. Nevertheless, the AGMG recommend eight stages separated by three hold points where results are documented and reviewed: (1) planning, conceptualisation and model design (based on clear objectives), (2) model construction, calibration and sensitivity analysis, (3) prediction and uncertainty analysis, and (4) final reporting and archiving. This modelling process can easily be applied to sitewide integrated balance modelling, of course recognising that calibration is not always possible in early stage studies.

The importance of data

It is useful to distinguish between "monitoring" of levels, flows and water quality in natural surface water and groundwater, often managed by EHS personnel, and "metering" of levels, flows and water quality in engineered parts of a mine site, with data sometimes collected by Supervisory Control and Data Acquisition (SCADA) systems and stored in large database systems such as AVEVA PI System (previously known as OSIsoft PI Historian). It takes substantial effort to access both types of data, if indeed it is necessary. This depends on the question being addressed.

A bigger challenge in studies and even during operations is simply to obtain the mining schedule, the schedule for production of waste rock, the processing schedule and the tailings production schedule, to support a planned QRA. Sometimes the "poor cousin" needs to educate and encourage all the teams involved in a study, to allow integrated water, mass and solute modelling to succeed.

Conclusions

This paper is not intended to teach modellers how to develop models. Rather the author hopes to have provided some context and referred to many challenges, to help young modellers, experienced modellers and those who need to read and understand model predictions to gain perspectives on how the current state-of-the-art has evolved to where it is today.

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