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Spacing, Scheduling, and Scaling:

Field Development Planning for Stratiform Evaporite Solution Mining

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Abstract

Field development in stratiform evaporite deposits presents a distinct challenge in solution mining: how to efficiently extract resources across broad horizontal areas while maintaining long-term geomechanical stability and managing surface infrastructure requirements. Unlike domal salt formations, which support vertically oriented cavern designs with relatively independent wellheads, stratiform deposits force operators to make tightly coupled decisions about spacing, scheduling, and scaling. However, despite the growing number of projects targeting these bedded salt deposits, few technical publications offer planning frameworks specific to their constraints.

This paper presents a practical, field-oriented guide for optimizing cavern placement and development in horizontally extensive, thinly bedded, solution mineable evaporite formations. Drawing from real-world projects and engineering experience, the tradeoffs between cavern spacing, pillar width, drilling cost, and resource recovery were examined. Subsurface layout options and operational considerations are discussed herein, highlighting their implications for subsidence risk and long-term stability. In parallel, surface infrastructure factors such as flow distribution, water sourcing, and pad placement efficiency were also evaluated, which interact closely with drilling and leaching schedules.

To illustrate the framework, screening tools have been introduced for recovery factor estimation, subsidence risk assessment, and hydraulic performance. These examples show how technical checks can be integrated early in the planning phase to guide design decisions. Supported by visual schematics and development flow summaries, this framework highlights where adjustments in spacing, scheduling, or scaling can be adopted to minimize costly redesigns and improve project outcomes.

This paper synthesizes planning strategies and layout principles drawn from multiple projects and operational experience. By linking technical and operational considerations, it provides decision tools broadly applicable to large-scale solution mining in stratiform evaporite settings.

Key words: Bedded Salt Deposits, Cavern Design, Cavern Development, Cavern Spacing, Field Development Planning, Rock Mechanics, Solution Mining, Salt, Subsidence, Trona

Background: Field Development in Stratiform Evaporites

Historically, salt domes have received substantial technical attention in solution mining because their thick, concentrated resources yield large quantities of salt, and they are widely used in building storage caverns. These domes are concentrated in specific geologic provinces; therefore, their distribution is geographically limited [U.S. Department of Energy, 2022].

In contrast, evaporite resource mapping shows that laterally extensive bedded deposits occur across much broader regions worldwide, as depicted in Figure 1 [Horváth et al., 2018]. With the sustained industrial demand for evaporite minerals (e.g., halite, trona) for use in chemical manufacturing, glass production, and de-icing, efficient development of these resources is increasingly important [U.S. Geological Survey, 2025].

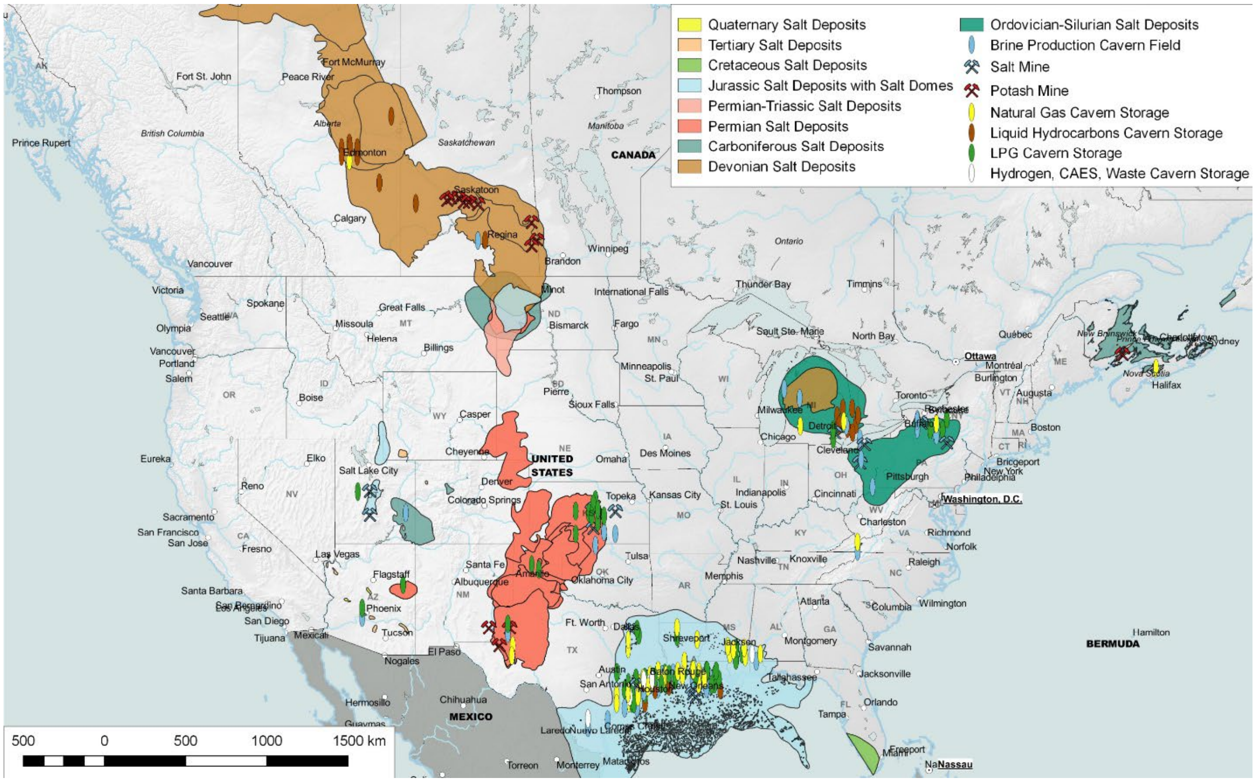

Figure 1. Distribution of Major Salt Deposits Across the Continental United States and Canada. While some deposits host caverns developed for hydrocarbon and natural gas storage, these resources extend far beyond storage applications, representing a large base for mining and industrial use (after Horváth [2018]).

Stratiform evaporites are formed when saline water bodies such as seas, lakes, or lagoons evaporate, leaving behind mineral-rich sediments [Warren, 2016]. Historically, these deposits were exploited through underground mining or, less commonly, vertical solution-mined wells.

Before directional drilling gained popularity in unconventional oil and gas development in the early 2010s, solution-mined wells were typically drilled vertically into thin evaporite beds. This approach was often less economical than similar operations within thicker salt deposits. After the availability of directional and horizontal drilling technologies became widespread, these methods were increasingly applied in solution mining projects to reach greater lateral extents from fewer surface locations, thus improving access to thin but laterally continuous beds.

Stratiform evaporites are generally thinner than domal deposits and are interbedded with insoluble layers, such as limestone, anhydrite, shale, marlstone, or volcanic tuffs [Dyni, 1996]. These interbeds constrain cavern geometry and influence stress distribution. Additionally, the need for higher cavern counts per project increases the likelihood of mechanical and hydraulic interactions across the field. Because caverns can extend significant distances horizontally from their wells, illustrated in Figure 2, the potential for these interactions is amplified compared to operations in domal salt.

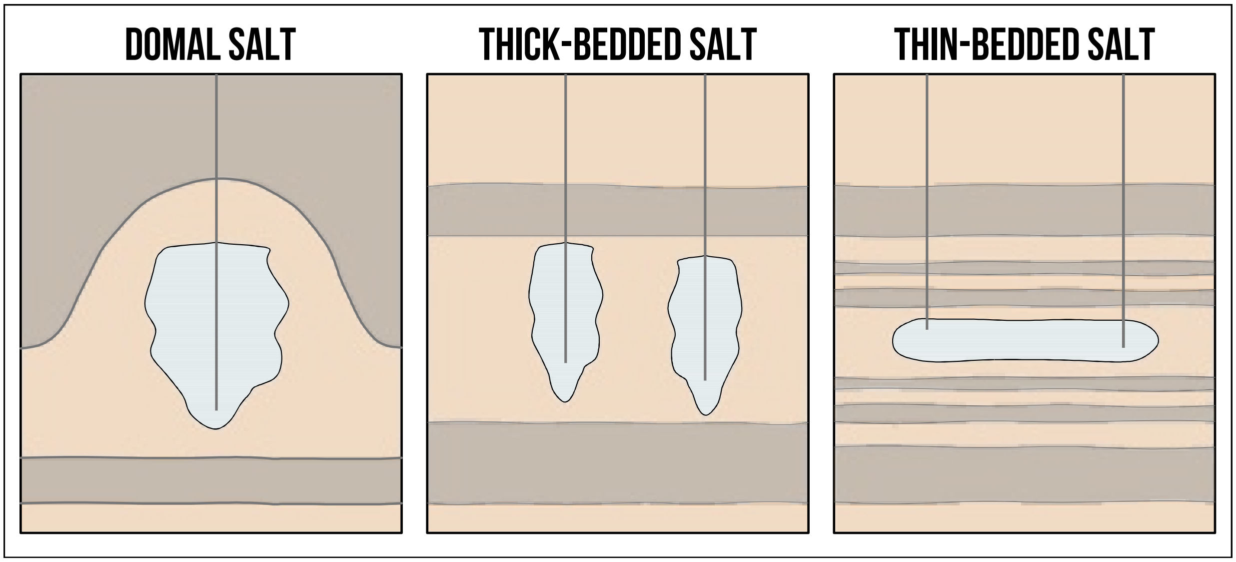

Figure 2. Domal and Thick-Bedded Salt Deposits Lend Themselves to Tall Caverns. Thin-bedded salt caverns are more conducive to lateral cavern designs.

These characteristics create a distinct planning challenge, as efficient recovery in stratiform evaporites depends heavily on well placement, cavern spacing, and sequencing. A systematic, integrated approach to these factors is essential in balancing recovery efficiency, cost control, and geomechanical stability of bedded evaporite settings.

Gap in Current Planning Approaches

Field development in stratiform evaporite deposits poses planning challenges that differ fundamentally from those in domal salt or thicker evaporite beds. Because stratiform resources are laterally extensive but thin, production targets require numerous relatively small caverns. This geometry forces close cavern spacing, coordinated scheduling of parallel operations, and incremental scaling across a broad surface footprint.

Most of the planning approaches available in literature were developed for thick, relatively uniform salt formations with caverns that are taller and fewer than those in stratiform and are largely independent in behavior, excluding the gas storage projects. These previous models provide limited guidance for managing the tight dependency between subsurface stability, surface infrastructure, and operational sequencing that dominate stratiform projects.

Without a framework specifically for thinly bedded evaporites, operators risk using designs that compromise recovery efficiency, geomechanical stability, or long-term scalability. This paper addresses that concern by presenting a practical planning approach that integrates spacing, scheduling, and scaling decisions for solution mining in stratiform evaporites.

Spacing Considerations

In stratiform evaporite solution mining, cavern spacing determines both the distance between cavern units and the placement of wells within each unit. Cavern units are long panels of caverns linked to each other. A typical cavern unit may consist of one or two vertical wells connected by a horizontal well, which forms a single hydraulic and mechanical system. Design decisions regarding unit spacing and injector/producer separation should balance recovery, geomechanical stability, and surface efficiency.

The following well configurations also shape cavern spacing and unit layout in stratiform deposits:

- Single-well caverns offer higher control over geometry and flow paths and are simple to operate, but generally require several wells because of the limited surface area that can be leached per well. Roof height control may also pose a challenge.
- Dual-well caverns (i.e., one injector and one producer) introduce more surface area that can be leached at the sacrifice of shape control. These caverns can generally achieve higher recovery efficiency compared to single caverns, but flow paths tend to concentrate between the wells. Maintaining uniform geometry is slightly more challenging compared to single caverns, making spacing decisions more sensitive to long-term stability concerns.
- Multi-well caverns (i.e., three or more wells) expand flexibility by allowing alternating injection and production points, but they introduce additional complexity. Preferential flow paths can emerge, leading to uneven dissolution and irregular cavern development. When more wells are added, maintaining a predictable cavern shape and stable flow between units becomes difficult.

In thin, laterally extensive beds, spacing and configuration tradeoffs must be balanced carefully. Experience suggests that the preferred configuration often emphasizes long-term stability and field-wide uniformity over maximizing short-term recovery, although optimal approaches may vary. Numerical modeling studies of bedded salt formations show that cavern spacing must be carefully considered for stratiform deposits (e.g., [Bruno, 2005]).

Parameters Defining Spacing Geometry

The following five primary parameters govern the cavern unit layout in stratiform solution mining projects:

- **Pillar width-to-height (W/H) ratio**: The normalized pseudo-factor of stability across layouts.
- **In-row well spacing**: The distance between the injector and producer wells within a unit. Well spacing influences the cavern shape, as shown in Figure 3, and recoverable reserves. Spacing also influences the produced brine concentrations in the early phases of cavern development.
- **Target cavern diameter**: The desired diameter of the cavern. The targeted cavern diameter affects the final leached size, as shown in Figure 4. However, the diameter is constrained by geology, geomechanical, and operational factors.
- **Unit-to-unit spacing**: The center-to-center distance between adjacent units. Increased distance between units improves geomechanical stability at the expense of reduced recovery per unit area, as shown in Figure 5.
- **Cavern orientation – square vs. staggered**: The spatial relationship between the individual caverns. Square layouts use a 90-degree spacing in rows and columns, and staggered (hexagonal) layouts offset caverns at 60 degrees (increasing density and altering stress distribution), as shown in Figure 6.

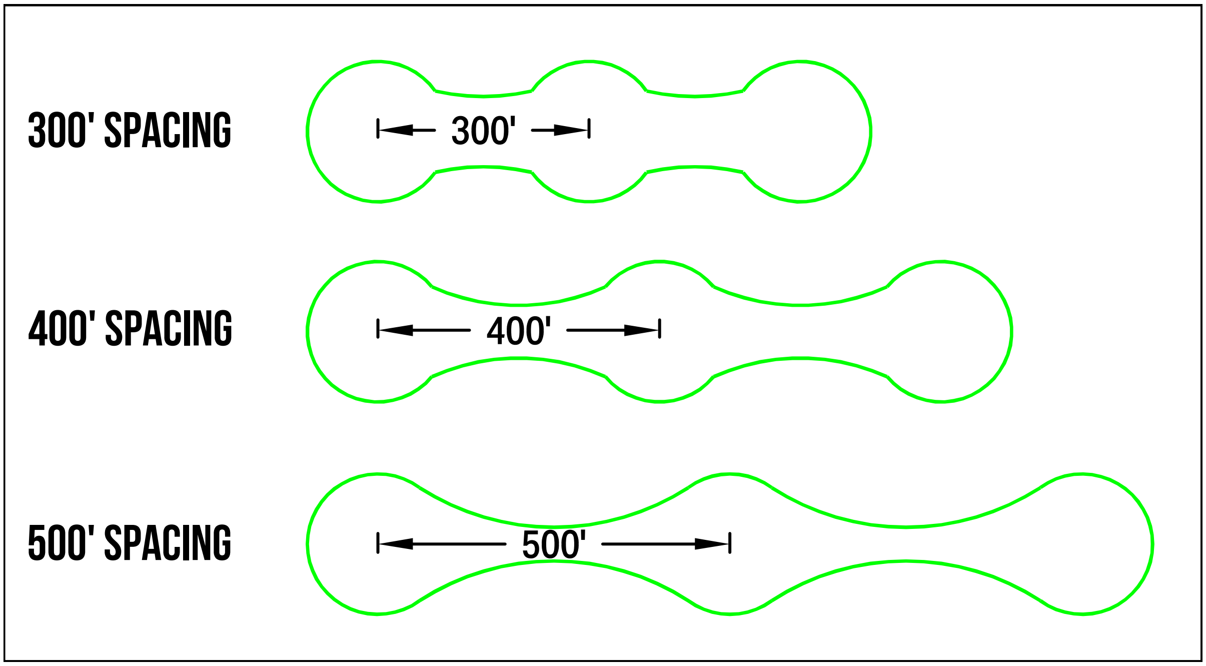

Figure 3. Cavern Geometry Under Different Injector/Producer Well Spacings (300, 400, and 500 Feet). When the wells are placed further apart, the cavern becomes leaner (i.e., more elongated across its width) [Öztürk, 2024].

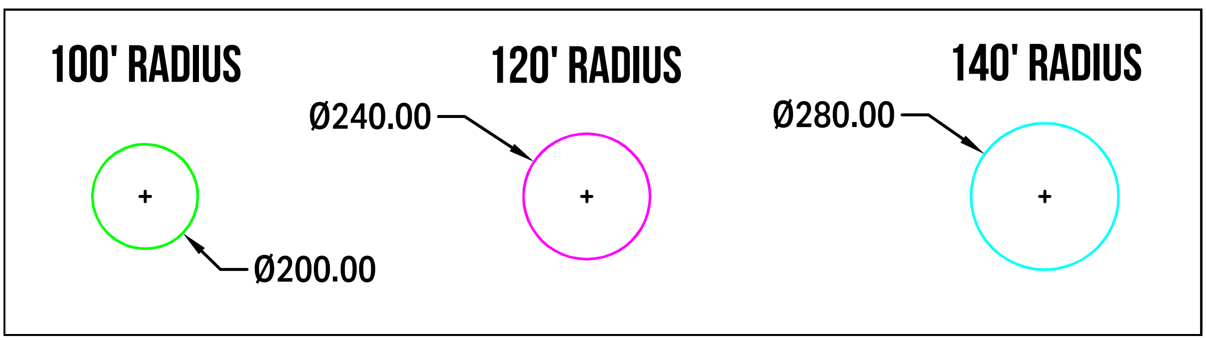

Figure 4. For Stratiform Caverns Where Height is Essentially Fixed, Cavern Volume Scales With the Square of Diameter. Increasing the diameter from 200 to 280 feet (a 40% increase) nearly doubles the leached volume.

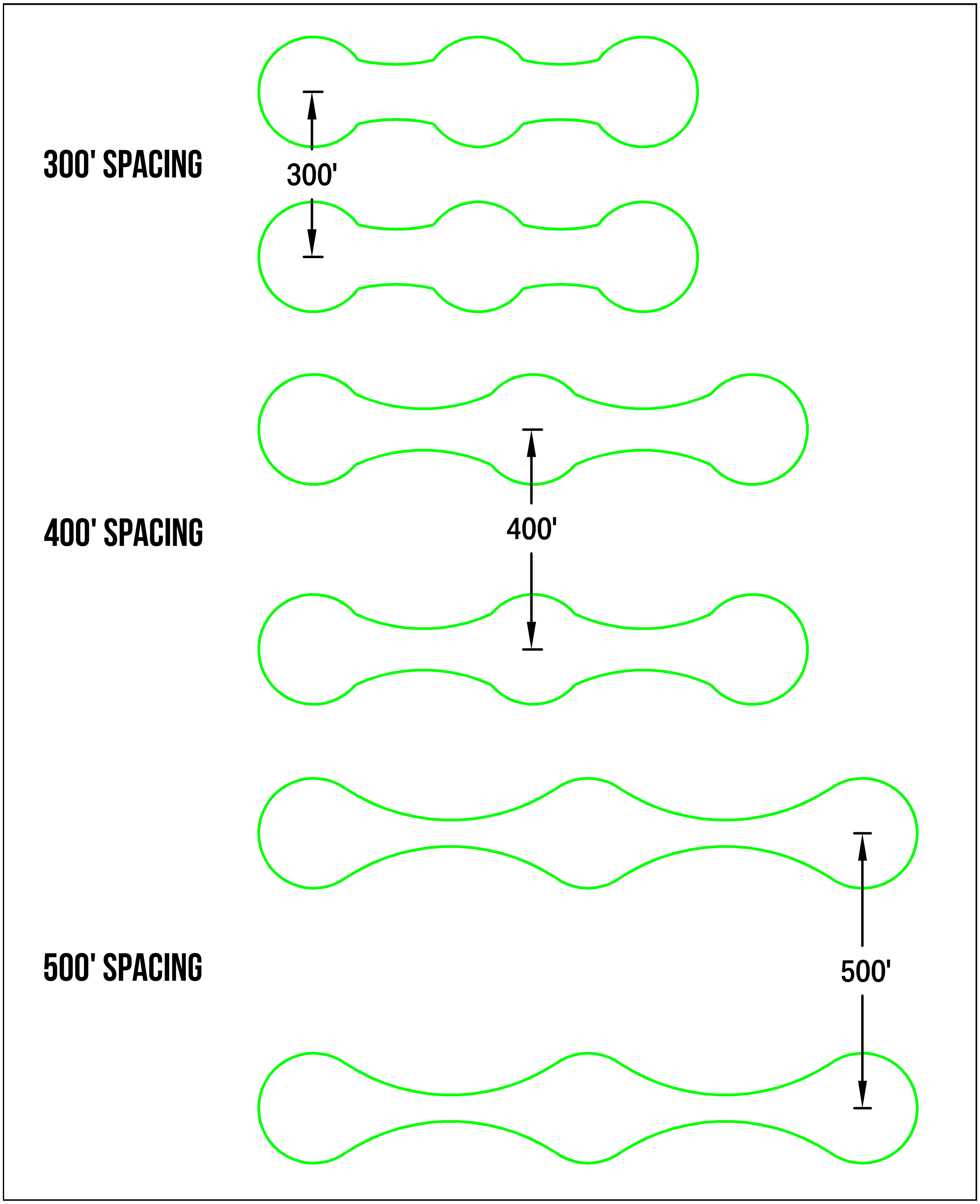

Figure 5. Cavern Geometry Shown at Unit-to-Unit Spacings of 300, 400, and 500 Feet. Increasing spacing enlarges the salt pillar between caverns, trading recovery for greater stability.

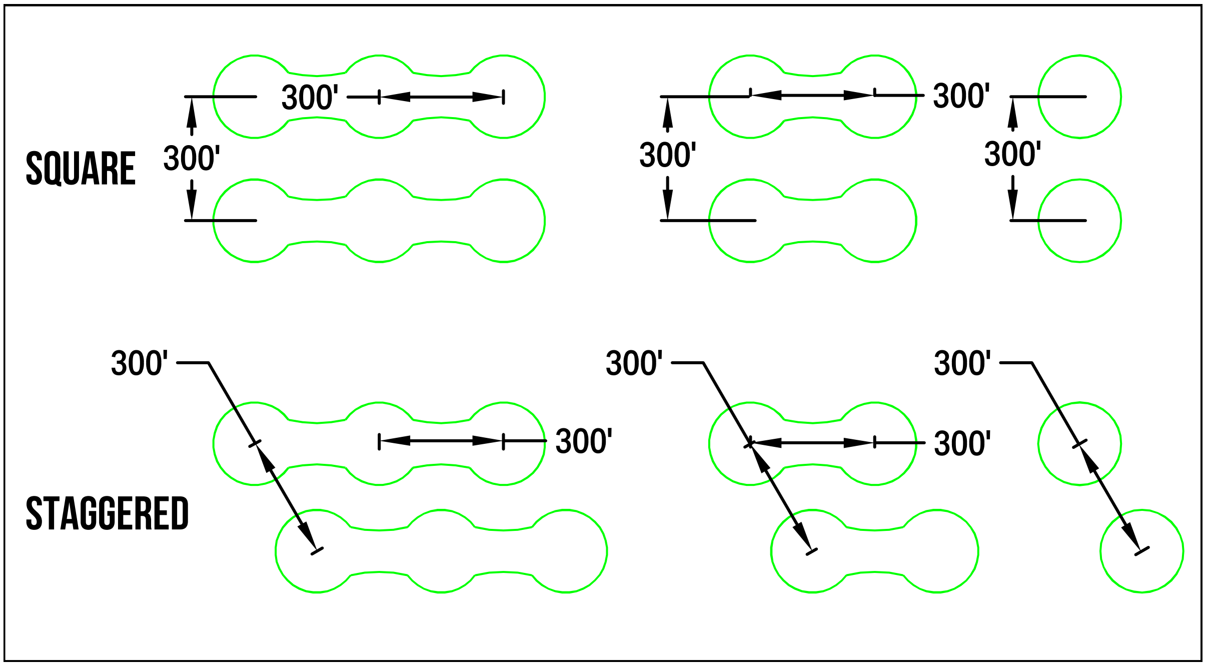

Figure 6. Comparison of Cavern Unit Placement Patterns. The square (orthogonal) spacing maintains uniform pillar width in two directions, while the staggered (hexagonal) spacing increases effective pillar separation diagonally, potentially improving stability at equivalent center-to-center spacing by keeping a more uniform pillar thickness.

Geomechanical Implications

Narrower pillars may increase the risk of cavern coalescence, accelerate stress redistribution, and complicate the control of cavern shape and flow.

Numerical modeling confirms that reduced pillar W/H ratios correspond to greater instability and higher subsidence potential compared to increased W/H ratio, particularly when multiple caverns are developed in close proximity [Cai et al., 2024]. Pillar geometry also governs the magnitude and areal extent of surface subsidence.

In practice, some degree of stress redistribution may occur over time, depending on creep behavior of the minerals and the development sequence. Layering leaching schedules is occasionally used to moderate pillar loading when spacing is tight or W/H ratios are low.

Production Effects

Close cavern spacing increases recovery by reducing unmined pillar volume, although it also narrows the stability margin. Staggering the caverns increases recovery by allowing more caverns to be implemented and creating a more uniform pillar thickness between units.

Within a cavern unit, a wider injector/producer spacing can increase residence time during early leaching and promote broader dissolution. Conversely, short injector/producer distances risk preferential flow paths and early breakthrough. Numerical modeling of brine circulation supports this effect, showing that the injection geometry strongly influences concentration distribution and cavern growth uniformity [Wang et al., 2023].

Economic and Surface Implications

Spacing decisions can also shape project economics, as a tighter cavern placement reduces trunkline length, lowers pumping distance, and improves the use of shared surface facilities. Additionally, close spacing can defer pad expansion by concentrating early development around shorter corridors. Conversely, wider spacing requires a larger surface footprint and more extensive infrastructure to achieve the same production targets.

From an operating perspective, compact layouts can reduce per-cavern surface cost and may improve concurrency with construction and tie-ins. Wider spacing increases unit infrastructure costs and expands the disturbed surface area, which can add permitting complexity and long-term land management obligations. These choices not only influence capital expenditures but also operations and maintenance efficiencies throughout the field's life.

Implications for Scheduling and Scaling

Spacing choices set the framework for both scheduling and long-term scaling. Close spacing may require sequenced leaching to reduce simultaneous loading on adjacent pillars. Wider spacing can accommodate later infill drilling, relieving the stress concentrations. However, wider spacing may force an early surface expansion to sustain production targets.

Step-out expansion strategies concentrate on early development by minimizing the initial infrastructure length, although they rely on tight cavern placement within each stage. Because surface footprint growth follows the cavern layout, spacing decisions also affect permitting and environmental approvals. As detailed in the Scheduling the Development Section, these outcomes must be coordinated with cavern development sequencing to balance geomechanical stress redistribution and resource demand.

Synthesis of Spacing Decisions

Spacing in stratiform evaporites connects geometry, stability, economics, and surface layout with the timing and scale of field development. Close spacing can improve recovery and reduce early infrastructure needs, but also increases geomechanical risk and requires careful sequencing. Although wider spacing reduces these risks and preserves infill opportunities, it increases surface impact and capital requirements. The most effective strategies preserve flexibility for both infill and step-out expansion, ensuring that projects can adapt as operating conditions and resource demands evolve.

Scheduling the Development

Scheduling in stratiform evaporite solution mining governs the sequence and timing of drilling, leaching, and infrastructure construction. Unlike domal projects with few, vertically isolated caverns, stratiform fields depend on the coordinated development of several small, interconnected caverns. This effort makes each scheduling decision critical to production ramp-up, capital pacing, infrastructure utilization, and geomechanical stability [Hansen et al., 2016].

An effective schedule manages concurrency across drilling rigs, injection pumps, and construction crews, while coordinating water demand, brine handling, and permitting windows. Schedule management also links short-term cavern activation to long-term expansion, ensuring operational risks and resource constraints are balanced from the outset. The following subsections outline how development modes, geomechanical timing, and operational factors shape scheduling strategies in stratiform fields.

Interdependencies and Development Modes

In stratiform deposits, caverns share the pumps, headers, and water sources, which causes the caverns to perform interdependently. Coordinating the large number of caverns required to meet production targets depends on aligning drilling, leaching, and surface facilities from the beginning.

The following five factors define the scheduling framework:

- **Development mode:** Caverns may be advanced in parallel, sequence, or through a hybrid approach, setting the overall pace of expansion.
- **Pad activation pattern:** Expansion can progress from a central core, advance in block-by-block segments, or extend along corridors, as demonstrated in Figure 7.
- **Drilling and leaching concurrency:** Drilling may overlap with leaching to accelerate startup or be staged to reduce strain on infrastructure.
- **Leaching profile:** The rate and duration of leaching in each cavern govern both the initial production ramp-up and the long-term timeline.
- **Infrastructure pacing:** The speed at which trunklines, pumping stations, and headers are extended or upgraded influences how quickly new capacity can be brought online.

These factors are interconnected, and the choices made early in development strongly influence the amount of flexibility the project retains for future adjustments.

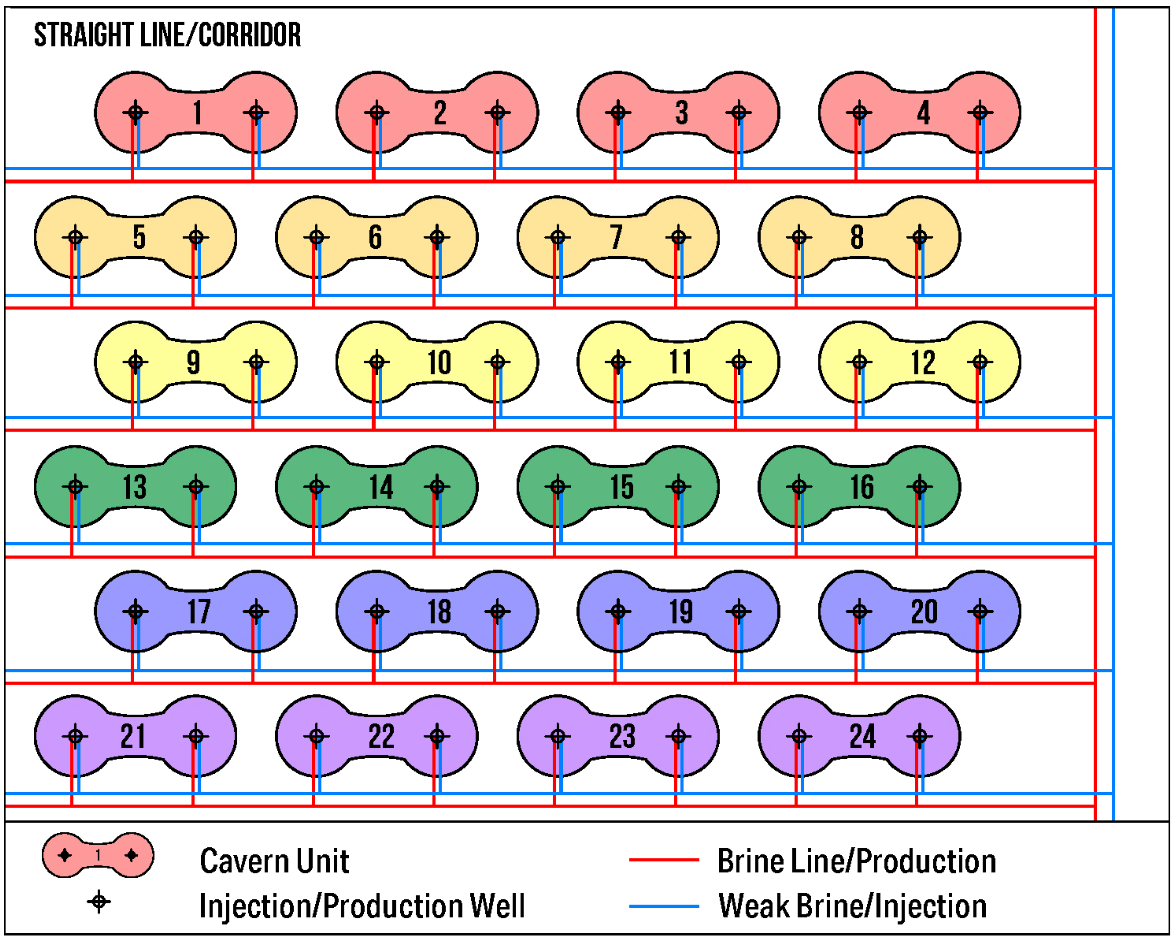

Figure 7. Corridor Development Layout Showing Sequential Rows Of Caverns. This arrangement allows surface infrastructure to be built gradually, but it can create logistical challenges when multiple crews operate in a confined area.

Geomechanical Timing Considerations

Geomechanical risks are closely tied to the sequencing of cavern development. Initiating leaching in adjacent caverns simultaneously can increase the potential rate and severity of subsidence and place additional stress on shared pillars. The time-dependent deformation behavior of most evaporitic rocks allows stresses to redistribute over time. Sequencing when each cavern development begins, as shown in Figure 8, takes advantage of this property, thus reducing peak loading and supporting stability.

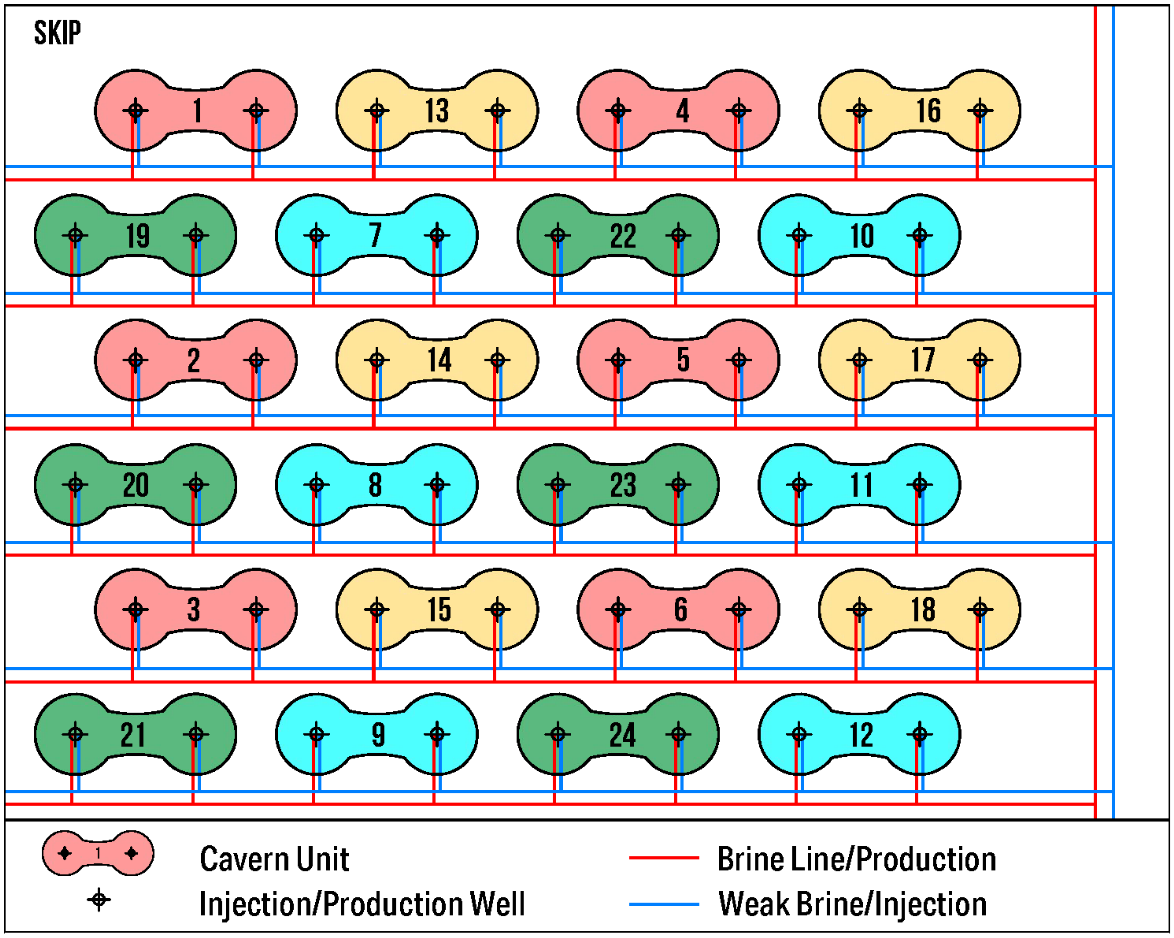

Figure 8. Skipped-Set Development Layout. Caverns are brought online in alternating positions rather than sequential corridors, distributing leaching stresses more evenly across the field. This approach can improve geomechanical conditions and reduce interaction risks, although it complicates surface piping and scheduling.

This effect becomes most important when pillar W/H ratios fall below 1.0. Although modeling studies of bedded salt formations show that cavern stability is sensitive to development sequence and spacing [Li et al., 2023], site-specific validation is essential. Scheduling should, therefore, be considered one of several tools available to influence stress redistribution patterns and manage geomechanical performance over the life of the field.

Operational Constraints and Resource Competition

Scheduling also governs use of the workforce, equipment, and field systems. The number of active rigs, pumps, and field crews directly drives fluctuations in labor demand and service coordination. Local impacts, such as traffic, noise, and housing competition, can add further constraints and influence the number of operations that can proceed at once.

Water and brine management are equally sensitive to scheduling. Water demand varies with the number of wells being drilled and caverns under active leaching, and requirements grow as caverns enlarge and void space increases. Early-stage leaching often produces weak brine, particularly in lower-solubility minerals. Managing this stream may involve providing temporary storage, blending with more concentrated flows, or recirculating into other caverns. Aligning infrastructure build-out with these changing volumes helps prevent idle assets and premature capital expenditure.

Economic and Regulatory Factors

Economic drivers strongly shape scheduling strategies. A rapid ramp-up may shorten the time to first revenue but requires high early capital expenditure. Although a staged approach spreads costs more evenly, it delays returns. The timing of these expenditures, not only their total amount, influences cash flow and determines how resilient the project is to setbacks.

Regulatory frameworks add another layer of constraint. Permitting timelines, water rights, land-use approvals, and environmental reviews can all dictate the sequence in which pads are developed, regardless of technical readiness. Delays in these approvals often determine the pace of expansion as much as engineering considerations.

Because economics and permitting interact closely with subsurface design and surface infrastructure, scheduling choices must be coordinated with spacing and scaling from the outset. Treating these elements as an integrated process ensures that capital phasing, regulatory sequencing, and field development logic remain aligned over the life of the project.

Integrating Scheduling into Field Development

Scheduling in stratiform evaporite mining extends beyond setting a timeline, requiring integration of the drilling capacity, leaching performance, water supply, regulatory pacing, and capital timing into a coordinated plan. Parallel and sequential approaches offer their own advantages, but only when matched with the necessary available resources and site conditions. Regulatory sequencing and economic constraints often define the pace of development as much as engineering considerations, while geomechanical timing helps manage subsidence and pillar loading risks.

Because these elements are tightly linked, scheduling must be treated as a planning lever alongside spacing and scaling. Effective schedules not only guide day-to-day operations but also preserve flexibility for future adjustments as conditions evolve. By integrating scheduling into the broader development framework, operators can balance stability, economics, and long-term growth in a way that supports both near-term production and sustainable field performance.

Scaling for Incremental Growth

Scaling in stratiform evaporite solution mining refers to the planned increase in production capacity over the life of a project through the addition of new caverns, pads, and supporting infrastructure. This scaling sets the long-term growth trajectory and determines how mined brine volumes expand to match processing plant throughput.

Thicker deposits can support step-change increases in capacity after surface facilities are established; however, thin, laterally extensive beds demand a more incremental approach. In these stratiform settings, scaling is continuous, with production rising in stages as caverns are added and surface systems extended.

Role of Scaling in Stratiform Fields:

Scaling serves as the framework for how a field grows from initial startup to full production. Scaling also determines the rate at which new caverns are added, how quickly water and brine systems must expand, and when processing upgrades are required. By defining the project's growth curve, scaling establishes the outer limits within which scheduling decisions are made. Thus, scaling acts as a strategic lever guiding investment pace and long-term capacity, while scheduling operates within these boundaries to manage short-term sequence and timing.

Drivers of Scaling Pace

The following four factors establish how quickly production capacity can expand in stratiform fields:

- **Growth strategy:** The pace at which new caverns or pads are brought online determines how rapidly production rises. Faster growth accelerates investment returns but demands higher upfront capital and strains resources, while slower growth reduces early exposure but delays full output.
- **Unit increment:** The volume added per cavern or pad defines the size of each step. Smaller increments allow more flexible matching of production targets but require frequent additions. Larger increments improve efficiency but reduce the ability to fine-tune capacity. Some growth models, such as batch development shown in Figure 9, make managing growth more predictable; however, as with other variables, it requires forethought in implementation.
- **Infrastructure phasing:** Water supply, brine headers, and pumping systems can be sized for end-state capacity from the outset or expanded in stages. Oversizing raises early costs, while undersizing risks holdups if growth outpaces upgrades.
- **Processing and resource alignment:** Field outputs must remain consistent with plant intake, contractor capacity, and available workforce. Expanding faster than processing capability or service capacity leads to inefficiencies and delays.

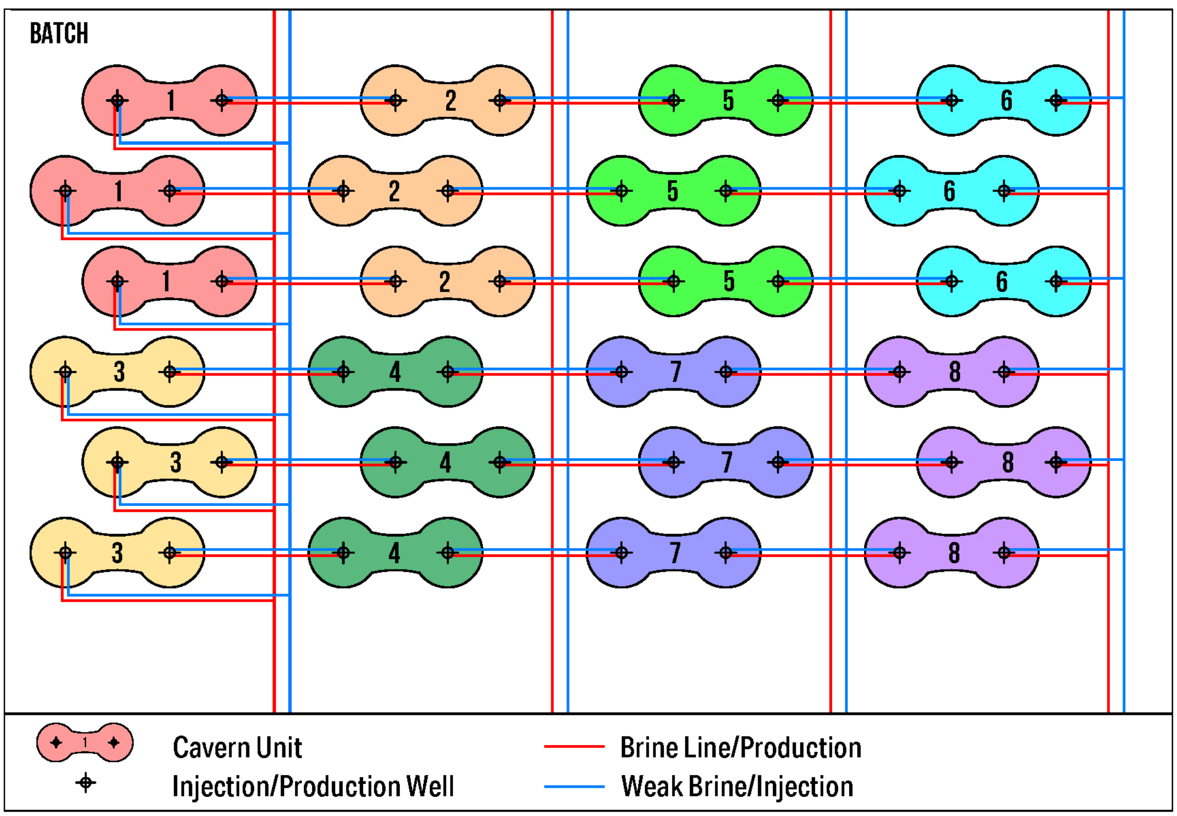

Figure 9. Batch Development Layout. Caverns and surface infrastructure are advanced in modular groups, making scaling more predictable in cost and timing. This approach simplifies replication but offers less logistical flexibility and reduced adaptability to site-specific stability conditions.

These drivers set the trajectory of scaling. Because early choices on unit size and infrastructure phasing often define a path that is difficult to reverse, scaling strategies must be framed with long-term production and investment goals in mind.

Operational and Resource Implications

As scaling advances, operational demands rise in step with the number of active caverns. Workforce and contractor requirements expand as more rigs, pumps, and leaching systems are mobilized, shifting the challenge from day-to-day coordination to sustaining a larger, more permanent operational footprint. Local housing capacity, access roads, and service logistics can become limiting factors as the field footprint grows.

Water and brine management also scale cumulatively. Each new cavern increases total injection demand and enlarges the overall void space that must be filled. Because several caverns will begin leaching at different times, the field will consistently produce a mix of weak and mature brines. The aggregate volume of weak brine grows with the number of early-stage caverns, creating a larger requirement for blending, recirculating, or providing temporary storage than would be apparent when looking at a single cavern in isolation.

As the cavern fleet expands, the probability of overlapping services or downtime events also rises. While not a near-term planning constraint, acknowledging this cumulative exposure helps ensure scaling strategies remain realistic over the full project life.

Geomechanical and Economic Tradeoffs

Scaling introduces both technical and financial pressures that must be considered together. From a geomechanical perspective, increasing the number of active caverns raises cumulative subsidence and field-wide stress. Adding large blocks of capacity in quick succession can concentrate deformation, while a more gradual trajectory provides time for stresses to redistribute and stabilize. These effects become more pronounced as the field footprint grows and multiple pads operate concurrently.

Economic tradeoffs follow a similar pattern. Rapid scaling can shorten the path to higher revenues but requires substantial upfront capital and exposes the project to higher concurrent operating costs. A slower approach spreads investment and labor needs over time, but risks underutilizing infrastructure and delaying cash flow.

Balancing these competing demands is central to effective scaling. The most robust strategies evaluate geomechanical stability alongside investment pacing, ensuring that capacity growth is both technically sustainable and financially resilient.

Integrating Scaling into Field Development

Scaling choices establish the trajectory for stratiform project growth, from startup to full production. These choices determine whether expansion proceeds in measured increments or aggressive steps and if new capacity can reliably be matched to infrastructure and processing limits. Once infrastructure and cavern development are in place, scaling pathways become costly and difficult to adjust, which makes early decisions especially important.

Because scaling interacts directly with spacing and scheduling, it must be treated as one of the three core planning levers; spacing establishes the physical room for growth, scheduling governs the order of operations, and scaling defines the pace and magnitude of capacity added. Integrating these elements provides a balanced framework that aligns geomechanical stability with economic resilience and long-term production goals.

Technical Analysis Tools

The factors and variables previously outlined offer initial guidance when beginning a greenfield project; however, aligning them with project development requires engineering calculations. This section introduces three tools that assist with early-stage decisions. These tools were selected based on their significant impact on the long-term performance of the project, although they do not represent all available options. This section also discusses how the cavern geometry influences recovery, cavern placement affects surface subsidence risk, and well feature sizing impacts the hydraulic efficiency of production circulation.

Recovery Factor Estimation

This tool estimates the proportion of in-place minerals that may be economically recovered within a cavern layout, which is subject to validation against field data and site-specific conditions. A baseline is given using the geometric recovery factor (GRF). The GRF is defined as the ratio of leached cavern volume to the mineralized rock volume encompassed by that geometry. Adjustments can then be applied to account for zones that are irregularly leached, have roof or bottom losses, and are rounded caverns, thus yielding a more realistic recovery estimate. The following information is required for this tool to function:

- **Inputs:** Cavern geometry (length, radius, height) is used to determine the volumetric recovery, mineral grade, and shape factors. Leaching efficiency can be integrated to establish a more realistic recovery factor.
- **Outputs:** A recovery factor (percentage) with sensitivity to geometry and well configuration is calculated.
- **Planning relevance:** The calculated results inform the efficiency of cavern placement (spacing), benefits of staging adjacent cavern development (scheduling), and effectiveness of resource yield across the field (scaling).

The impacts of well and cavern spacing, field orientation, cavern radius, and cavern design were evaluated on a production basis. A representative cavern field was developed in AutoCAD, consisting of three caverns in width and nine caverns in length. The rectangular footprint enclosing this array was considered the total available area. For each geometric scenario, the cumulative cavern volume that met the specified criteria was calculated and compared against this footprint to determine the recoverable percentage. These recovery factors were then compared across the scenarios to assess the effect of changing individual geometric parameters.

Spacing

Center-to-center well spacings of 300 feet (ft) (approximately 91.5 meters [m]), 400 ft (approximately 122.0 m), and 500 ft (approximately 152.5 m) were analyzed. Keeping all other variables consistent, the increase in well spacing decreased recoverability with 100-ft (30.5-m) radius caverns. This trend was consistent across all scenarios, although the specific recoveries were variable. The scenarios comprised the following parameters:

- 3-Well Cavern, Spacing: 300 ft (~91.5 m), Square: 30.4%
- 3-Well Cavern, Spacing: 400 ft (~122.0 m), Square: 22.7%
- 3-Well Cavern, Spacing: 500 ft (~152.5 m), Square: 17.3%

Orientation

The placement of wells in square (orthogonal) patterns and staggered (hexagonal) patterns was analyzed. Keeping all other variables consistent, a staggered orientation allowed for a higher recoverability compared to the square pattern, but not by a large margin. This trend was consistent across all scenarios, although the specific recoveries were variable. The scenarios comprised the following parameters:

- 3-Well Cavern, Radius: 100 ft (~30.5 m), Spacing: 400 ft (~122.0 m), Square: 22.7%
- 3-Well Cavern, Radius: 100 ft (~30.5 m), Spacing: 400 ft (~122.0 m), Staggered: 24.9%

Radius

Well radii of 100 ft (approximately 30.5 m), 120 ft (approximately 36.6 m), and 140 ft (approximately 42.7 m) were analyzed. Keeping all other variables consistent, the increase in well radius resulted in an increase in recoverability. This trend was consistent across all scenarios, although specific recoveries were variable. The scenarios comprised the following parameters:

- 3-Well Cavern, Radius: 100 ft (~30.5 m), Spacing 400 ft (~122.0 m), Square: 22.7%
- 3-Well Cavern, Radius: 120 ft (~36.6 m), Spacing: 400 ft (~122.0 m), Square: 27.6%
- 3-Well Cavern, Radius: 140 ft (~42.7 m), Spacing: 400 ft (~122.0 m), Square: 33.9%

Unit Design (Number of Wells)

Cavern designs featuring one, two, and three wells were analyzed. Keeping all other variables consistent, the 1-well cavern design had the highest recovery, the 3-well cavern design had a medium recovery, and the 2-well cavern design had the lowest recovery. This trend was consistent across all scenarios, although specific recoveries were variable. The scenarios comprised the following parameters:

- 3-Well Cavern, Radius: 100 ft (~30.5 m), Spacing: 400 ft (~122.0 m), Square: 22.7%
- 2-Well Cavern, Radius: 100 ft (~30.5 m), Spacing: 400 ft (~122.0 m), Square: 19.0%
- 1-Well Cavern, Radius: 100 ft (~30.5 m), Spacing: 400 ft (~122.0 m), Square: 24.9%

The individual case results highlight how spacing, orientation, radius, and cavern design each influence recovery in isolation. To capture their combined effect, all of the scenarios were compiled into a single comparative set. Table 1 summarizes how recovery factors varied across spacing distances, well configurations, and cavern radii. This table also illustrates the main tradeoffs: close spacing increases recovery but reduces pillar width, staggered orientations yield modest gains, and larger diameters drive the most substantial increases.

Table 1. Summary of All Parametric Calculations of the Recovery Factors Presented.

Orientation	Spacing (ft / m)	100-ft (~30.5-m) Radius			120-ft (~36.6-m) Radius			140-ft (~42.7-m) Radius		
		3 Wells (%)	2 Wells (%)	1 Well (%)	3 Wells (%)	2 Wells (%)	1 Well (%)	3 Wells (%)	2 Wells (%)	1 Well (%)
Square	300 / ~91.5	30.4	24.9	40.8	–	–	–	–	–	–
Square	400 / ~122.0	22.7	19.0	24.9	27.6	23.8	34.1	–	–	–
Square	500 / ~152.5	17.3	14.9	16.8	20.8	18.4	23.2	25.3	22.8	30.3
Staggered	300 / ~91.5	33.5	27.1	39.2	–	–	–	–	–	–
Staggered	400 / ~122.0	24.9	20.6	23.8	30.3	25.7	32.7	37.1	32.0	42.6
Staggered	500 / ~152.5	19.0	16.0	16.0	22.7	19.7	22.1	27.6	24.5	29.0

Cell shading indicates relative recovery factor: green = higher values, yellow = moderate values, and red = lower values. Configurations that produced a pillar W/H ratio <0.5 were excluded from the table.

In some situations, single-well caverns appeared to recover more resources because they could be placed closer together than two- or three-well caverns, which required a buffer distance for horizontal well construction. In this example, a build rate of 10 degrees per 100 ft (approximately 30.5 m) was assumed, requiring about 573 ft (approximately 174.7 m) of lateral distance to achieve the vertical-to-horizontal transition. Other scenarios followed the same trends, although some differences may have been muted by the variability introduced with this geometric constraint.

From this exercise, a few general principles emerged. Large-diameter caverns consistently extract more mineral volume than small-diameter caverns, staggered layouts provide small efficiency gains over square patterns, and wide spacings lower recovery but improve stability margins. These trends are merely instructive, and every project must be evaluated individually to identify an optimal cavern layout.

Subsidence Risk Estimation

This tool evaluates long-term geomechanical stability by considering how cavern placement and pillar geometry may affect subsidence and cavern interaction. The pillar W/H ratio is an initial screening measure of load-bearing adequacy; however, more detailed approaches, such as stress distribution modeling, creep convergence projections, or adjacency analyses, are recommended to account for site-specific conditions [Cyran and Kowalski, 2024]. The following information is required for this tool to function:

- **Inputs:** Cavern height, spacing, salt thickness, depth, and host rock properties are compiled to establish the basis for subsidence risk screening.
- **Outputs:** W/H ratio, estimated surface subsidence, and risk classification for pillar yielding or cavern coalescence are generated to identify stability thresholds and potential interaction risks.
- **Planning relevance:** These screening methods can be used to recommend minimum cavern spacing, inform safe sequences for cavern activation, and estimate threshold values for maximum cavern density within a field. However, final parameters should be validated through site-specific modeling and ongoing monitoring, as optimal values may vary based on local geology and operational history.

Subsidence risk estimation is an essential tool for predicting and analyzing the impacts of cavern placement and pillar geometry on overlying formations, aquifers, and, most importantly, the land surface. Excessive subsidence above solution-mined caverns can cause a range of negative effects, including disruption of natural drainage patterns, problematic changes in ground slope, development of surface fissures, and formation of localized subsidence pits. Each of these surface expressions is associated with one or more underlying mechanisms: changes in vertical elevation, accumulation of horizontal strain, and induced surface tilt.

To illustrate the influence of field and cavern layouts on potential subsidence behavior, series of baseline simulations were conducted using SALT_SUBSID, which is a numerical code developed by RESPEC for the Solution Mining Research Institute [Nieland, 1991]. The simulations were intentionally designed with conservative assumptions to bound the range of expected outcomes. Cavern development was represented by the instantaneous excavation of 3 cavern volumes per year, continuing until a total of 48 caverns was reached, corresponding to development over several years. Caverns were arranged in a six-by-eight grid according to the given orientation, with overall field dimensions ranging between 2,200 and 3,500 ft (670 to 1,070 m) on the north–south and east–west axes, depending on spacing and orientation. The three-well layout simulations also included a 600-ft (183-m) central well-to-well span to accommodate the directional well path. The annual volumetric closure of cavern volumes was modeled at a constant 0.5 percent per year, which is higher than typically observed in stratiform evaporite operations that maintain adequate brine pressure. Subsidence was calculated over a 50-year period (2025 to 2075) using an isotropic influence function appropriate for the generalized geologic conditions considered in this framework.

From the legitimate layout combinations defined in Table 1, 22 representative cases were selected that captured the limits of cavern radius, spacing, and well-activation scenarios. The results are reported in Table 2 (maximum vertical subsidence rate in ft/yr [m/yr]) and Table 3 (cumulative surface displacement in ft [m] by 2075). The blank cells in these tables indicate excluded combinations where the pillar W/H ratio fell below 0.5.

Collectively, these results establish bounding values that can be used to compare alternative field layouts and evaluate how cavern size, spacing, and activation mode shape subsidence potential.

Table 2. Simulated Maximum Vertical Subsidence Rates

Orientation	Spacing (ft / m)	100-ft (~30.5-m) Radius		120-ft (~36.6-m) Radius		140-ft (~42.7-m) Radius	
		3 Wells (ft/yr)	1 Well (ft/yr)	3 Wells (ft/yr)	1 Well (ft/yr)	3 Wells (ft/yr)	1 Well (ft/yr)
Square	**300 / ~91.5**	-0.020	-0.024	–	–	–	–
Square	**400 / ~122.0**	–	–	-0.023	-0.028	–	–
Square	**500 / ~152.5**	-0.013	-0.015	-0.019	-0.022	-0.026	-0.030
Staggered	**300 / ~91.5**	-0.021	-0.025	–	–	–	–
Staggered	**400 / ~122.0**	–	–	-0.025	-0.030	-0.034	-0.041
Staggered	**500 / ~152.5**	-0.014	-0.017	-0.021	-0.024	-0.028	-0.033

Cell shading indicates relative subsidence risk: green = lower values, yellow = moderate values, and red = higher values. Blank cells indicate combinations not included in the fractional factorial design or excluded for excessively small pillar widths.

Table 3. Simulated Maximum Vertical Subsidence Displacement by 2075

Orientation	Spacing (ft / m)	100-ft (~30.5-m) Radius		120-ft (~36.6-m) Radius		140-ft (~42.7-m) Radius	
		3 Wells (ft)	1 Well (ft)	3 Wells (ft)	1 Well (ft)	3 Wells (ft)	1 Well (ft)
Square	**300 / ~91.5**	-0.84	-1.03	–	–	–	–
Square	**400 / ~122.0**	–	–	-1.00	-1.19	–	–
Square	**500 / ~152.5**	-0.57	-0.66	-0.82	-0.95	-1.12	-1.29
Staggered	**300 / ~91.5**	-0.88	-1.07	–	–	–	–
Staggered	**400 / ~122.0**	–	–	-1.07	-1.27	-1.45	-1.73
Staggered	**500 / ~152.5**	-0.62	-0.72	-0.89	-1.03	-1.21	-1.40

Cell shading indicates relative subsidence risk: green = lower values, yellow = moderate values, and red = higher values. Blank cells indicate combinations not included in the fractional factorial design or excluded for excessively small pillar widths.

The simulation results show that both the maximum vertical subsidence rate and the 50-year cumulative displacement generally increase as the extraction ratio increases. Across the evaluated cases, maximum subsidence displacement ranged from 0.57 ft (0.17 m) to 1.73 ft (0.53 m). Published research on acceptable limits for surface infrastructure, particularly pipelines, suggests that vertical subsidence displacement should be limited to about 1 ft (approximately 0.3 m) to avoid damage to pipeline systems [Van Sambeek,2000]. Based on this threshold, cases with high extraction ratios and large excavation volumes, such as those involving a 140-ft (43-m) cavern radius or a closely packed 120-ft (37-m) cavern radius, represent conditions where surface infrastructure complications from expected subsidence behavior become more likely. These scenarios should, therefore, be approached with caution, especially where sensitive pipelines or other critical surface facilities are present within the area of influence.

Hydraulic Performance and Tubular Sizing

This tool ensures that well designs can support the planned injection and production flow rates without excessive hydraulic losses. Pressure drops are estimated using standard fluid mechanics (e.g., Darcy-Weisbach equation [White, 2016]) and expressed in terms of allowable flow bands for each tubing size. This effort identifies thresholds where a change in tubular design or surface equipment becomes necessary. The following information is required for this tool to function:

- **Inputs:** Flow rate, tubing internal diameter and length, brine density and viscosity, allowable pressure drop are compiled to define the operating envelope of each tubing option.
- **Outputs:** Recommended tubing size per flow band, expected pressure drop, and design limits for cavern depth or lateral reach are generated to guide well design and equipment selection.
- **Planning relevance:** This information links the well design to cavern geometry (spacing), informs operational tie-ins and flow balancing (scheduling), and defines when major infrastructure upgrades are triggered (scaling).

To demonstrate this tool in practice, a simplified example of a representative cavern system was prepared. The cavern was assumed to be laterally long (approximately 800 ft [244 m] between injection and recovery wells) and 2,500 ft (approximately 762 m) deep. The cavern was considered sufficiently developed so that its internal flow resistance was negligible compared to the tubing, making the well strings the dominant hydraulic constraint.

Selected Parameters:

- Flow rates: 10, 30, and 50 cubic meters per hour (m^3/hr) (~44, 132, and 220 gallons per minute [gpm])
- Tubing sizes: 3.5-, 4.5-, 5.5-inch (89-, 114-, and 140-millimeter [mm]) outer diameter (OD)
- Tubing length: 2,500-ft injection + 2,500-ft production = 5,000 ft (1,525 m)
- Brine density: 10.07 pounds per gallon (1.21 grams per cubic centimeter [g/cm^3])
- Brine viscosity: 1.2 centipoise (cP)
- Pressure loss calculated using Darcy–Weisbach equation (smooth-wall assumption)

The analysis demonstrates that tubing diameter is a primary control on the operating envelope of a solution mining well. Smaller diameters can provide acceptable performance during early or pilot-scale operations, but become increasingly restrictive as flowrates increase, leading to higher hydraulic resistance and energy demand. Intermediate diameters offer balanced performance, maintaining efficiency across a wider range without the construction penalties of the largest sizes. Larger diameters provide the greatest operating flexibility but require higher initial investment. The results shown in Table 4 indicate that while multiple configurations may be technically viable at lower throughputs, beyond a certain threshold upsizing becomes essential to sustain production without exceeding practical pumping limits or operating costs.

Tubing selection also establishes the casing dimensions and hole sections, thus creating a cascade of construction impacts. Large tubing requires a large production casing, which often propagates to increased intermediate and surface strings.

- **Compact design (3½-inch [89-mm] tubing):** 3½-inch (89-mm) tubing → 5½-inch (140-mm) production casing in 7⅞-inch (200-mm) hole → 8⅝-inch (219-mm) intermediate → 11¾-inch (298-mm) surface.

- **Upsized design (4½-inch [114-mm] tubing):** 4½-inch (114-mm) tubing → 7-inch (178-mm) production casing in 8½-inch (216-mm) hole → 9⅝-inch (244-mm) intermediate → 13⅜-inch (340-mm) surface.

Each step-up increases the casing tonnage, cement volumes, and drilled footage. In one representative comparison, upsizing from 3½-inch (89-mm) to 4½-inch (114-mm) tubing raised the total steel requirements by about one-third and the drilled volume by roughly 30%, with the surface casing alone adding close to 50% more steel.

Table 4. Frictional Pressure Losses Across Typical Tubing Sizes at Representative Solution Mining Flow Rates.

Tubing OD (in / mm)	Tubing ID (in / mm)	Weight (lb/ft / kg/m)	Flow (m^3/hr / gpm)	Velocity (ft/s / m/s)	ΔP (psi / kPa)
3.5 / 89	3.068 / 78	7.7 / 11.5	10 / 44	1.91 / 0.58	12.3 / 84.8
			30 / 132	5.73 / 1.75	87.5 / 603.3
			50 / 220	9.55 / 2.91	219.8 / 1,515.3
4.5 / 114	4.090 / 104	9.5 / 14.1	10 / 44	1.08 / 0.33	3.1 / 21.5
			30 / 132	3.23 / 0.98	22.0 / 152.0
			50 / 220	5.38 / 1.64	55.2 / 380.6
5.5 / 140	4.950 / 126	15.5 / 23.1	10 / 44	0.72 / 0.22	1.3 / 8.7
			30 / 132	2.20 / 0.67	8.8 / 60.9
			50 / 220	3.68 / 1.12	22.1 / 152.3

ID = inner diameter
lb/ft = pounds per foot
kg/m = kilograms per meter
m/s = meters per second
ft/s = feet per second
psi = pounds per square inch
kPa = kilopascal

These higher upfront requirements must be weighed against potential operating benefits. Large tubing reduces frictional pressure losses, reduces pumping head, and improves the overall efficiency of brine circulation systems. For projects with deep wells or high sustained flow rates, these efficiency gains may offset part of the added construction burden when evaluated over the full lifecycle of a field.

The planning tradeoff is, therefore, two-sided:

- Compact designs minimize drilling and casing cost but risk increased hydraulic resistance and limited flexibility at scale.
- Upsized designs increase initial construction effort but provide increased hydraulic efficiency and reserve operating capacity for high flow regimes.

Thus, what may appear as a construction penalty at the well scale can become a field-level advantage when considered alongside hydraulic performance, operating efficiency, and long-term development needs.

Additional Tools

While this paper focuses on subsurface placement and cavern geometry, the following complementary tools could be incorporated to extend the framework into a more comprehensive field development model:

- **Cavern interaction screening:** Applies spacing criteria or elastic radius checks to flag potential interference. These screening methods guide early layout choices before detailed geomechanical modeling.
- **Flow balance and mixing analysis:** Evaluates blending of weak and mature cavern brines to stabilize plant feed chemistry and coordinate commissioning of new caverns with production schedules.
- **Pad and surface footprint optimization:** Compares cavern density with pad count, surface corridors, and infrastructure needs to minimize land-use and construction impacts.
- **Water and energy demand forecasting:** Provides project cumulative water and power requirements as caverns are added, linking flow targets to pump sizing and utility planning.

These tools are most directly tied to scheduling and scaling and are less central to this study's spacing focus. Incorporating these additional tools would extend the framework into a full field development model that integrates surface and subsurface constraints.

Field Planning Framework

Field development in stratiform evaporite deposits for solution mining requires a planning process that links subsurface layout, geomechanical stability, surface infrastructure, and operational sequencing. These deposits are laterally extensive and often thinly bedded, meaning production depends on several relatively small caverns. Close spacing, combined with interaction through the host rock and shared infrastructure, makes thorough planning essential. Any adjustment in spacing, scheduling, or scaling can affect cost, operational performance, and long-term stability.

The framework presented herein is intended as a practical roadmap rather than a prescriptive design template. Its role is to guide early decision-making, highlight points of interaction between choices, and flag common risks before they become costly to address. By treating key geological and operational parameters as ranges rather than fixed values until they can be confirmed by reliable field measurements and sampling, the framework ensures that uncertainty is carried forward explicitly and decisions remain robust as new data become available.

Baseline Definition

Planning begins with defining the resource and operating context. Bed thickness, interbeds, and overburden properties determine cavern height and pillar geometry, while production targets, water supply, and plant capacity set the scale of development. Within this baseline, parameters such as creep rate, interbed strength, or dissolution efficiency should be recognized as uncertain inputs, and their influence on stability and recovery must be tested across their expected ranges. This approach keeps early designs realistic and avoids false precision until field data provide tighter constraints.

Preliminary Spacing Concept

With the baseline in place, spacing concepts can be drafted and tested against geomechanical criteria, such as pillar W/H ratio, minimum well separation, and target cavern diameters. These choices balance recovery against stability while also shaping the density of the surface footprint. To make these assumptions defensible, spacing should be anchored to an explicit geomechanical design basis. For example, the field may be designed under a no-damage criterion, an acceptable subsidence threshold, or a specified design life. Initially defining this basis clarifies the philosophy behind spacing decisions and provides consistency when they are later tied to hydraulic checks, scheduling, and scaling pathways.

Hydraulic Feasibility

Hydraulic capacity needs to be verified early to ensure that tubing, casing, and pumps can sustain the flow rates implied by cavern size and spacing. Feasibility checks should test the ranges of flow, pressure, and tubing diameter to confirm that circulation can be maintained without excessive frictional loss or pump head. Identifying hydraulic limits at this stage prevents late redesigns of the wells or surface systems and reduces the risk of holdups that can affect the entire field plan. By linking hydraulic performance directly to the spacing concept, planners can confirm that the chosen layout is achievable with practical well designs and equipment sizes.

Surface Integration

Subsurface layouts must be translated into surface infrastructure that accounts for pad siting, trunkline routing, and utility tie-ins. This step reconciles cavern geometry with access, constructability, and regulatory setbacks. Directional drilling may reduce surface disturbance by consolidating wells onto fewer pads, but it introduces added cost and operational complexity that must be weighed carefully. Early integration of surface and subsurface design minimizes the risk of costly land-use conflicts or permitting delays once development is underway.

Scheduling Logic

The sequence of drilling, completion, and leaching determines how production expands and how stresses accumulate in the subsurface. Schedules should align cavern activation with plant capacity while staggering adjacent wells to limit simultaneous pillar loading. Concurrency across rigs, pumps, and crews must remain realistic for local logistics, and water demand should be matched to the number of caverns under active leaching. Regulatory approvals often shape timing as much as technical readiness, so sequencing must also accommodate the time needed for permitting efforts. Well-designed schedules not only reduce risks of subsidence and holdups but also provide a lever to pace investment and preserve flexibility for later expansion.

Scaling Pathway

Scaling defines how field capacity grows beyond initial development. In stratiform deposits, growth is incremental, with production rising in stages as caverns and supporting infrastructure are added. Early choices regarding pad size, header routing, and corridor spacing strongly influence the ease of integrating new capacity. Undersized systems risk holdups, while oversizing drives up early capital. A scaling pathway that preserves options for step-out or infill drilling ensures the project can expand steadily while adapting to changes in demand, resource conditions, or regulatory limits.

Iteration and Calibration

Field planning is inherently iterative, and assumptions made early must be tested against actual performance. As caverns are developed, data such as sonar surveys, brine chemistry, pressure behavior, and subsidence monitoring should be used to calibrate geomechanical and hydraulic models. This feedback loop improves the reliability of forecasts and keeps the framework aligned with real conditions rather than initial estimates. By treating iteration as a model calibration rather than a simple review, the framework becomes a living tool that evolves with the project, reducing the risk of compounding errors and improving confidence in long-term planning decisions.

Framework Synthesis

Framework brings structure to the complex task of planning solution mining in stratiform evaporites. The framework begins with a baseline that treats key parameters as ranges, advances through spacing concepts tied to a stated design basis, and incorporates hydraulic and surface checks to keep layouts practical. Scheduling and scaling decisions are then aligned with capacity growth and regulatory pacing, while iterative calibration ensures that the models evolve with field data. Together, these elements provide a roadmap that connects technical rigor with adaptability, helping operators balance recovery, stability, and long-term efficiency.

Discussion

The proposed framework adds value by structuring how spacing, scheduling, and scaling are considered together rather than as isolated decisions. This framework highlights interactions that often remain implicit in conventional planning, such as how cavern density influences surface corridor design or how sequencing decisions affect stress redistribution across shared pillars. By carrying uncertainty forward as ranges until it can be narrowed with field data, the framework avoids the false precision that can undermine early-stage designs. Explicitly stating a geomechanical design basis further strengthens its defensibility, ensuring that assumptions regarding allowable subsidence or pillar stress are transparent rather than implied.

However, the framework is not a tool for optimization. It provides structure and prompts the right questions, but it does not resolve tradeoffs quantitatively or prioritize among competing objectives such as cost, recovery, and stability. This limitation is not unusual for planning methods at the conceptual stage, but it does leave outcomes dependent on the judgment and discipline of the project team. This framework also assumes regular updates and data integration; without active calibration to sonar, subsidence, or hydraulic performance measurements, it risks becoming static and losing its value as a living tool.

The conditions for success are straightforward but nontrivial. A minimum dataset is required, including credible stratigraphy, overburden properties, hydraulic performance curves, and production targets. Decision thresholds such as maximum allowable subsidence or pillar stress must be clearly established; otherwise, spacing assumptions remain arbitrary. Equally important is a monitoring plan that ensures data are collected, shared, and acted upon in a consistent way across drilling, cavern engineering, and surface infrastructure teams. When these requirements are met, the framework can function as a common reference point that keeps subsurface and surface planning aligned.

This framework is best suited to stratiform evaporites where several small caverns must be coordinated across broad areas. In these settings, individual design choices quickly propagate into field-scale consequences, and a structured approach helps prevent local optimization from creating global problems. In domal salt or thick uniform evaporites, where caverns behave more independently, the benefits are less pronounced. Compared with current practice, which often develops caverns piecemeal and expands infrastructure reactively, the framework shifts planning toward anticipation and system-level coherence. Although it does not eliminate uncertainty or guarantee the best plan, this framework does improve transparency, support adaptability, and help operators recognize the tradeoffs inherent in large-scale field development.

Conclusion

This paper has introduced a field planning framework tailored specifically to stratiform evaporite deposits, where development depends on numerous small caverns and the tight dependency of subsurface and surface systems. Unlike approaches adapted from domal salt, this framework provides a structured process that treats spacing, scheduling, and scaling as interdependent levers rather than isolated design steps.

The framework does not resolve tradeoffs quantitatively, nor is it a substitute for detailed geomechanical modeling. The effectiveness rests on reliable geological and operational data, clearly defined design criteria, and consistent calibration to field measurements. Where these conditions are in place, the framework offers practical value by preventing missteps that arise when decisions are made piecemeal and by maintaining coherence as projects expand.

Future work should build on this foundation by linking the framework to optimization and economic methods, but its current strength lies in structuring early planning decisions and exposing their consequences across the field. In that role, this framework provides not the perfect plan, but the discipline to keep plans coherent, adaptable, and defensible as stratiform solution mining moves from concept to long-term operation.

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