**Strategic Produced Water Management Optimization**

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Mathematical Notation

**Sets**

Time periods (i.e. weeks)

Well pads

Production pads (subset of well pads )

Completion pads (subset of well pads )

Freshwater sources

Disposal sites

Storage sites

Treatment sites

Reuse options

Network nodes

Locations (superset of well pads, disposal sites, nodes, …)

Pipeline diameters

Storage capacities

Injection (i.e. disposal) capacities

Production-to-completion pipeline arcs

Production-to-node pipeline arcs

Production-to-production pipeline arcs

Completion-to-node pipeline arcs

Completion-to-completion pipeline arcs

Node-to-node pipeline arcs

Node-to-completion pipeline arcs

Node-to-disposal pipeline arcs

Node-to-storage pipeline arcs

Node-to-treatment pipeline arcs

Node-to-reuse pipeline arcs

Freshwater-to-completion pipeline arcs

Treatment-to-node pipeline arcs

Treatment-to-disposal pipeline arcs

Storage-to-node pipeline arcs

Storage-to-completion pipeline arcs

Storage-to-disposal pipeline arcs

Storage-to-treatment pipeline arcs

Storage-to-reuse pipeline arcs

Production-to-completion trucking arcs

Freshwater-to-completion trucking arcs

Production-to-disposal trucking arcs

Production-to-storage trucking arcs

Production-to-treatment trucking arcs

Production-to-reuse trucking arcs

Completion-to-disposal trucking arcs

Completion-to-storage trucking arcs

Completion-to-treatment trucking arcs

Completion-to-completion trucking arcs (flowback reuse)

Storage-to-completion trucking arcs

Storage-to-disposal trucking arcs

Treatment-to-disposal trucking arcs

**Continuous Variables**

Produced water piped from one location to another location

Produced water trucked from one location to another location

Fresh water sourced from source to completion pad

Water put into completions pad storage

Water removed from completions pad storage

Water level at storage site

Water level in completions pad storage

Total volume of water trucked

Total volume freshwater sourced

Total volume of produced water disposed

Total volume produced water reused

Cost of piping produced water from one location to another location

Cost of trucking produced water from one location to another location

Cost of sourcing fresh water from source to completion pad

Cost of injecting produced water at disposal site

Cost of treating produced water at treatment site

Cost of reusing produced water at completions site

Cost of storing produced water at storage site (incl. treatment)

Credit for retrieving stored produced water from storage site

Total cost of sourcing freshwater

Total cost of injecting produced water

Total cost of treating produced water

Total cost of reusing produced water

Total cost of piping produced water

Total cost of storing produced water

Total cost of trucking produced water

Total cost of slack variables

Total credit for withdrawing produced water

Disposal capacity in a given time period at disposal site

Storage capacity in a given time period at storage site

Flow capacity in a given time period between two locations

Capital cost of constructing or expanding disposal capacity

Capital cost of constructing or expanding piping capacity

Capital cost of constructing or expanding storage capacity

Slack variable to meet the completions water demand

Slack variable to process produced water production

Slack variable to process flowback water production

Slack variable to provide necessary pipeline capacity

Slack variable to provide necessary storage capacity

Slack variable to provide necessary disposal capacity

Slack variable to provide necessary treatment capacity

Slack variable to provide necessary reuse capacity

**Binary Variables**

New pipeline installed between one location and another location with specific diameter

New or additional storage facility installed at storage site with specific storage capacity

New or additional disposal facility installed at disposal site with specific injection capacity

Directional flow between two locations

Timing of pipeline installation between one location and another location with specific diameter

Timing of storage facility installation at storage site with specific storage capacity

Timing of disposal facility installation at disposal site with specific injection capacity

**Parameters**

Completions demand at a completions site in a time period

Total water demand over the planning horizon

Produced water supply forecast for a production pad

Flowback supply forecast for a completions pad

Total water production (production & flowback) over the planning horizon

Initial weekly pipeline capacity between two locations

Initial weekly disposal capacity at a disposal site

Initial storage capacity at a storage site

Storage capacity at completions site

Initial weekly treatment capacity at a treatment site

Initial weekly reuse capacity at a reuse site

Weekly freshwater sourcing capacity at freshwater source

Weekly truck offloading sourcing capacity per pad

Weekly truck offloading sourcing capacity per storage site

Weekly processing (e.g. clarification) capacity per pad

Weekly processing (e.g. clarification) capacity at storage site

Treatment efficiency at treatment site

Pipeline capacity installation or expansion increments

Disposal capacity installation or expansion increments

Storage capacity installation or expansion increments

Truck capacity

Disposal construction or expansion lead time

Storage construction or expansion lead time

Pipeline construction or expansion lead time

Drive time between two pads

Drive time from a pad to a disposal site

Drive time from a pad to a storage site

Drive time from a pad to a treatment site

Drive time from a pad to a reuse site

Drive time from a storage site to a completion site

Drive time from a storage site to a disposal site

Drive time from a treatment site to a disposal site

Initial storage level at storage site

Initial storage level at completions site

Terminal storage level at storage site

Terminal storage level at completions site

Pipeline segment length

Disposal construction or expansion capital cost for selected capacity increment

Storage construction or expansion capital cost for selected capacity increment

Pipeline construction or expansion capital cost for selected diameter

Disposal operational cost

Treatment operational cost (may include “clean brine”)

Reuse operational cost

Storage deposit operational cost

Storage withdrawal operational credit

Pipeline operational cost

Trucking hourly cost (by source)

Fresh sourcing cost

Big-M flow parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Slack cost parameter

Mathematical Program Formulation

**Objectives**

*(1) Minimize Costs*

*(2) Maximize Reuse*

**Completions Pad Demand Balance**

**Completions Pad Storage Balance**

**Completions Pad Storage Capacity**

**Terminal Completions Pad Storage Level**

**Freshwater Sourcing Capacity**

**Completions Pad Truck Offloading Capacity**

**Completions Pad Processing Capacity**

Note: this constraint has not actually been implemented yet.

**Storage Site Truck Offloading Capacity**

**Storage Site Processing Capacity**

**Production Pad Supply Balance**

**Completions Pad Supply Balance (i.e. Flowback Balance)**

**Network Node Balance**

**Bi-Directional Flow**

Note: Technically this constraint should only be enforced for truly reversible arcs (e.g. *NCA* and *CAN*); and even then it only needs to be defined per one reversible arc (e.g. *NCA* only and not *NCA* and *CAN*).

**Storage Site Balance**

**Terminal Storage Level**

**Pipeline Capacity Construction/Expansion**

Note: Parameter will be calculated as follows:

where is Hazen-Williams constant and is Hazen-Williams exponent as per Cafaro & Grossmann (2020) and represents the pipeline diameter as per the set .

**Storage Capacity Construction/Expansion**

**Disposal Capacity Construction/Expansion**

**Treatment Capacity**

**Treatment Capacity Construction/Expansion**

**Treatment Balance**

where

**Beneficial Reuse Capacity**

**Fresh Sourcing Cost**

**Total Fresh Sourced Volume**

**Disposal Cost**

**Total Disposed Volume**

**Treatment Cost**

**Completions Reuse Cost**

Note: Freshwater sourcing excluded from completions reuse costs.

**Total Reuse Volume**

**Piping Cost**

Note: the constraints above explicitly consider freshwater piping via FCA arcs.

**Storage Deposit Cost**

**Storage Withdrawal Credit**

**Trucking Cost (Simplified)**

Note: the constraints above explicitly consider freshwater trucking via FCT arcs.

**Total Trucking Volume**

**Disposal Construction or Capacity Expansion Cost**

**Storage Construction or Capacity Expansion Cost**

**Pipeline Construction or Capacity Expansion Cost**

**Slack Costs**

**Logic Constraints**

General Comments

* The optimization problem can be enhanced/complicated significantly IF capacity expansion/construction decisions are modeled being time dependent, i.e., the program not only determines whether a pipeline/storage/disposal facility is built but also WHEN that will occur. The most promising option would be to solve the time-independent design problem initially and then address the time-sensitive planning problem subsequently.
* At this time the framework is primarily geared towards the design and operation of a produced water pipeline network; does the model need to be expanded to consider (complex) freshwater pipeline networks too?
* Pad storage capacity is currently neglected. This assumption is tied to the weekly resolution of the planning horizon. Do we need to revisit this in case large pits are erected near completions pads that receive produced water deliveries over weeks, leading up to the begin of completions operations? Tentative workaround: create “separate” storage locations that are associated with completions sites.

Open Questions

* Should we include an “offloading” limits (trucking AND piping) for produced water deliveries (completion pads, storage sites and disposal sites)? This could include treatment bottlenecks at completion sites.
* Should “storage costs” include a cost term specifically dedicated to treating the water to “clean brine” specification?
* Should we develop a water scheduling model in addition to the water management model? Would a scheduling horizon be more suitable for Marcellus and/or DJ operations? Does that conflict with Revonos’ business model?
* How do we capture the treatment setups in the Permian and the DJ basins? Do we simply assume pad-based treatment pre-frac or central treatment with pad delivery?

Outstanding Items

* ~~Introduce slack variables where necessary or useful (especially: offloading/processing capacity constraints)~~