**Operational Produced Water Management Optimization**

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Mathematical Notation

**Sets**

Time periods (i.e. days)

Well pads

Production pads (subset of well pads )

Completion pads (subset of well pads )

Production tanks

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

Pad-to-tank links

**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

If model.config.production\_tanks == ProdTank.single:

Produced water drained from production tank

Water level in production tank

Elif: model.config.production\_tanks == ProdTank.equalized:

Produced water drained from equalized production tanks

Water level in equalized production tanks

Produced water for transport from pad

Water level in storage site

Water level in completions pad storage

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

If model.config.production\_tanks == ProdTank.single:

Produced water supply forecast for a production pad

Production tank capacity

Initial water level in production tank

If model.config.production\_tanks == ProdTank.equalized:

Produced water supply forecast for a production pad

Combined capacity of equalized production tanks

Initial water level in equalized production tanks

Flowback supply forecast for a completions pad

Note: Review the need for separate flowback forecasting at the pad level

Daily pipeline capacity between two locations

Daily disposal capacity at a disposal site

Storage capacity at a storage site

Storage capacity at completions site

Daily treatment capacity at a treatment site

Daily reuse capacity at a reuse site

Daily freshwater sourcing capacity at freshwater source

Daily truck offloading sourcing capacity per pad

Daily truck offloading sourcing capacity per storage site

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

Daily processing (e.g. clarification) capacity at storage 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 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 (does not include transportation 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

**Objective**

**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 Tank Balance**

If model.config.production\_tanks == ProdTank.single:

elseif model.config.production\_tanks == ProdTank.equalized:

**Production Tank Capacity**

If model.config.production\_tanks == ProdTank.single:

elseif model.config.production\_tanks == ProdTank.equalized:

**Terminal Production Tank Level Balance**

if model.config.production\_tanks == ProdTank.single:

elseif model.config.production\_tanks == ProdTank.equalized:

**Tank-to-Pad Production Balance**

if model.config.production\_tanks == ProdTank.single:

elseif model.config.production\_tanks == ProdTank.equalized:

Note: The constraint proposed above is obviously not necessary but included to facilitate switching between (1) an equalized production tank version and (2) a non-equalized production tank version.

**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**

**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**

**Beneficial Reuse Capacity**

**Fresh Sourcing Cost**

**Disposal Cost**

**Treatment Cost**

**Completions Reuse Cost**

Note: Freshwater sourcing excluded from completions reuse costs.

**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.

**~~Disposal Construction or Capacity Expansion Cost~~**

**~~Storage Construction or Capacity Expansion Cost~~**

**~~Pipeline Construction or Capacity Expansion Cost~~**

**Slack Costs**

**~~Logic Constraints~~**

General Comments

* Production tanks (aggregate or individual) are currently not modeled explicitly (i.e., storage levels, capacity, …)
* 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 any “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)~~