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# Evaluation and analysis of Forced Evaporation system for Oil & Gas Production facilities in Pakistan

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## ABSTRACT

*Produced water is the by-product of Oil & Gas processing plants. It is basically the waste product full of chemical contaminants; which cannot be utilized for any useful purpose. Produced water quality varies significantly based on geographical location, type of hydrocarbons produced, and the geochemistry of the producing formation. The types of contaminants found in produced water and their concentrations have a large impact on the most appropriate type of beneficial use and the degree and cost of treatment required. Afterwards, produced water techniques in the world were identified and discussed to take positive guidance towards establishing more viable solution to the increasing produced water volumes in the world in general and in Pakistan in particular. Each of the produced water handling techniques has pros & cons with respect to their implementation at site depending upon the volumes of it generated each day, it's chemical and physical characteristics etc. During the project, produced water data was gathered from Pakistani oil & gas companies; evaluated and analyzed accordingly to reach at a conclusion with respect to its most feasible and viable handling technique. Forced evaporation system was found to be the cheapest and most feasible form of handling produced water provided the volumes generated each day are in controlled range. As far as higher produced water generation is concerned, definitely other handling techniques such as water injection, water treatment, and down-hole injection for oil recovery are the alternate solutions to the problem. After analyzing the daily produced water generation rates in the subject operating companies, it was concluded in the end that by switching from conventional costlier produced water disposal techniques to the cheaper Forced Evaporation system would save millions of dollars. Brief comparison is provided for various operating companies across Pakistan using conventional vs. Forced Evaporation system for produced water disposal at their respective sites.*

**Keywords:** Production Facility, Produced water, Evaporation Pond, Forced Evaporation, Conventional disposal techniques.

## 1. INTRODUCTION

Produced water is defined as the water that exists in subsurface formations and is brought to the surface during oil and gas production [1]. Water is generated from conventional oil and gas production, as well as the production of unconventional sources such as coal bed methane, tight sands, and gas shale. The concentration of constituents and the volume of produced water differ dramatically depending on the type and location of the petroleum product. Produced water accounts for the largest waste stream volume associated with oil and gas production [2].

Produced water is the by-product of Oil & Gas processing plants. It is basically the waste product full of chemical contaminants; which cannot be utilized for any useful purpose. It cannot be drained in open water channel because it is the violation of local and international environmental laws. Actually, it's a hazard to the health of human beings, animals and plants due to chemical contamination. So, as per practice and legal obligations, it is the responsibility of the company to store it in ponds, utilize it for beneficial domestic/industrial uses or inject back into formation to prevent its drainage into the natural water channels, rain water channels etc.

Main objective of the subject project is to devise and implement method for safe and cheap handling of produced water generated from Oil & Gas production facilities in Pakistan. As hundreds of barrels of produced water is obtained daily from different oil & gas plants of these companies, thus, there is a strong need for devising, developing and implementing a mechanism to handle increasing rate of produced water from the subject companies. Data pertaining to the produced water production was gathered from different Oil & Gas companies operating in Pakistan including their method of produced water management. Eventually, Forced Evaporation system was discussed and evaluated in detail for handling produced water.

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### 2.1. Produced water management at MPCL

Mari Petroleum Company Limited (MPCL) is a premier company operating in Exploration and Production sector across Pakistan. Mari Petroleum Company Limited is operating the country's 2nd largest gas reservoir at Mari Field, District Ghotki at Sindh. The Shares of the Company are quoted on all the Stock Exchanges of Pakistan. The Company is primarily engaged in Exploration, development and Production of hydrocarbon potentials (Natural gas, Crude oil, Condensate & LPG) in the country. MPCL is also exploring opportunities of expanding its business to become a player in the International hydrocarbon Market.

Mari Petroleum Company Limited is currently engaged in operations at 5 oil and gas processing facilities located in Sindh and Baluchistan province. Following are the brief details of the produced water production rates and method of disposal for the same.

**Table 1: Produced water production & disposal techniques at MPCL**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Mari Petroleum Dharki | 500 | Well Injection |
| 2 | Mari Deep | 250 | Well Injection |
| 3 | Ghauri | 100 | Well Injection |
| 4 | Halini | 30 | Natural Evaporation |
| 5 | Zarghoun | 25 | Natural Evaporation |

**Mari Petroleum Company Limited (MPCL) Ghotki, Sindh [3]**

MPCL utilizes natural evaporation means for disposal of produced water because of quite low production rates. However, depending upon the increased production rates of produced water in near future, they might feel the need for employing some alternate disposal means as well to tackle the increased production rates.

### 2.2. Produced water management at PPL

The pioneer of the natural gas industry in the country, Pakistan Petroleum Limited (PPL) has been a frontline player in the energy sector since the mid-1950s. As a major supplier of natural gas, PPL today contributes over 20 percent of the country's total natural gas supplies besides producing crude oil, Natural Gas Liquid and Liquefied Petroleum Gas.

**Table 2: Produced water production & disposal techniques at PPL**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Sui | 1684 | Well Injection |
| 2 | Kandhkot | 230 | Well Injection |
| 3 | Aadhi | 120 | Well Injection |
| 4 | Mazrani | 10 | Natural Evaporation |
| 5 | Hala Gas | 12 | Natural Evaporation |

**Pakistan Petroleum Limited (PPL) [4]**

Table 2 clearly depicted in the above table, PPL is currently employing two different techniques for produced water handling at their operating fields. First method of disposal is well injection which is a bit costly mean of disposal of produced water. While the other one is natural Evaporation which is definitely one of the cheapest means of managing produced water in oil and gas sector.

### 2.3. Produced water management at OGDCL

OGDCL is the national oil & gas company of Pakistan and the flagship of the country's E&P sector. The Company is the local market leader in terms of reserves, production and acreage, and is listed on all three stock exchanges in Pakistan and also on the London Stock Exchange since December 2006. The Company is all set to ride the wave of E&P activity, equipped with its Vision & Mission, Business and Strategic Plan, a debt-free and robust balance sheet and healthy cash reserves. The Company is ready to take on the challenges of a volatile E&P industry.

**Table 3: Produced water production & disposal techniques at OGDCL**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Qadirpur | 2500 | Well Injection |
| 2 | Dhakni | 590 | Well Injection |

**Oil & Gas Development Company (OGDCL) [5]**

Table 3 tabulates the data pertaining to produced water generation and subsequent disposal method employed at OGDCL Pakistan in its fields located in Punjab. Total daily production of produced

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water is around 3090 barrels per day which is disposed off using Well Injection mode.

### 2.4. Produced water management at ENI

ENI has been operating in Pakistan since 2000. ENI Pakistan is the operator of the Bhit and Kadanwari gas producing fields, and is a partner in the third party operated fields of Zamzama, Sawan, Miano and Rehmat. With a yearly average net equity production of over 50,875 boepd ENI Pakistan ranks as the largest foreign producer in the Pakistan E&P sector. ENI Pakistan is the operator of Gorakh, Mithi, Rajar, Umarkot and Thar exploration Blocks onshore and has two offshore exploration licenses “M” & “N” in the Indus Delta. ENI Pakistan is also a partner in the Middle Indus onshore exploration Blocks of Mubarak, South West Miano, Gambat & Latif.

**Table 4: Produced water production & disposal techniques at ENI Pakistan**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Bhit, Train-1 | 300 | Well Injection |
| 2 | Bhit, Train-2 | 150 | Well Injection |
| 3 | Bhit, Train-3 | 150 | Well Injection |
| **ENI Pakistan Limited [6]** | | | |

Table 4 tabulates the data pertaining to produced water generation and subsequent disposal method employed at ENI Pakistan in its fields located in Sindh. Total daily production of produced water is around 600 barrels per day which is disposed off using Well Injection technique.

### 2.5. Produced water management at PEL

Petroleum Exploration Limited (PEL) is a private sector Exploration & Production company operating in Pakistan. It was established in 1994 and in short period became an active operator having largest acreage among top ten private sector operating companies in Pakistan. It is exploring on land and deep waters off-shore Pakistan. It is also the first Pakistani E&P Company operating and is currently carrying out exploration over three onshore permits in Morocco. Besides, it has also been granted two exploration blocks in Myanmar. PEL has a highly experienced E&P team with industry renowned experts. It is organized into multidisciplinary integrated teams and believes in optimally exploiting knowledge/technology by outsourcing to industry leaders.
It has twelve JV partners from Pakistan, Canada, Kuwait, UK, Morocco, and Australia, which includes BP, OGDCL, PPL, MPCL, Frontier Holding Limited, Gulf Petroleum Exploration, ONHYM, Sherritt, Spud, OGIL, Pyramid Energy International Incorporated BVI, Government Holding Private Limited.

**Table 5: Produced water production & disposal techniques at PEL Pakistan**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Shikarpur, Block-22 | 2300 | Well Injection |
| 2 | Kandra | 300 | Well Injection |
| 3 | Ghotki Badar | 25 | Natural Evaporation |
| **PEL Pakistan [7]** | | | |

Table 5 tabulates the data pertaining to produced water generation and subsequent disposal method employed at PEL Pakistan in its fields located in Sindh. Total daily production of produced water is around 2500 barrels per day which is stored in Evaporation Ponds without any further disposal mean for the same.

### 2.6. Produced water management at POL

Pakistan Oilfields Limited (POL) is a leading oil and gas exploration and production company listed on all the three stock exchanges of Pakistan. The Company's prime focus is to deliver performance through excellence in the field of exploration, drilling and production of crude oil and gas.
Pakistan Oilfields Limited (POL), a subsidiary of The Attock Oil Company Limited (AOC), was incorporated on November 25, 1950. AOC was founded in 1913 and made its first oil discovery in 1915 at Khaur, District Attock. AOC has, therefore, pioneered exploration and production of oil and gas in this region nearly a century ago. In 1978, POL took over the exploration and production business of AOC. Since then, POL has been investing independently and in joint venture with various exploration and production companies for the search of oil and gas in the country.
In addition to exploration and production of oil and gas, POL also manufactures LPG, Solvent Oil and Sulphur. POL markets LPG under its own brand named POLGAS as well as through its subsidiary CAPGAS (Private) Limited. POL also operates a network of pipelines for transportation of its own as well as other companies' crude oil to Attock Refinery Limited.
In 2005, the Company acquired a 25% share in National Refinery Limited, which is the only refining complex in the country producing fuel products as well as lube base oils.

**Table 6: Produced water production & disposal techniques at POL Pakistan**

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| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Miyal | 1000 | Well Injection |
| 2 | Khaur | 2500 | Well Injection |
| 3 | Pindori | 5000 | Well Injection |
| **Pakistan Oilfields Limited (POL) [8]** | | | |

Table 6 tabulates the data pertaining to produced water generation and subsequent disposal method employed at POL Pakistan in its fields located in Punjab. Total daily production of produced water is around 8500 barrels per day which is disposed off using Well Injection technique.

### 2.7. Produced water management at MOL Pakistan

A fully owned subsidiary of MOL Group is operating in Pakistan since 1999. MOL Pakistan has a very successful track record of operations in Pakistan where it has operated as well as non-operated joint ventures with the local E&P companies. MOL Pakistan is the Operator of the TAL, Margala and Margala North blocks and it has participation in two non-operated blocks namely Karak and Ghauri. It holds exploration area around 9,800 sq. km in various blocks whereas it has 465 sq.km acreage of the D&P lease area.
MOL Pakistan has managed to drill 10 exploratory wells, 5 appraisal wells and 9 developments wells in the Operated blocks till first quarter of 2014.
MOL Pakistan has 6 discoveries to its credit, namely Manzalai, Makori, Mami khel, Maramzai, Tolanj, and Makori East as operated, along with two discoveries namely Halini & Ghauri – operated by MPCL.

**Table 7: Produced water production & disposal techniques at MOL Pakistan**

| S. No | Field | Production (bbls) | Mode of disposal |
|---|---|---|---|
| 1 | Makori Production Facility | 550 | Natural Evaporation |
| 2 | Manzalai Gas Plant | 300 | Natural Evaporation |
| 3 | Central Processing Facility | 2000 | Natural Evaporation |
| 4 | Makori Gas Pressing Facility | 1000 | Natural Evaporation |
| **MOL Pakistan Oil & Gas Co. [9]** | | | |

Table 7 tabulates the data pertaining to produced water production and subsequent disposal method employed at MOL Pakistan in its fields located in KPK. Aggregate daily production of produced water is around 3850 barrels per day which is naturally evaporated in Evaporation Ponds.

### 3.1. Forced Evaporation system as produced water disposal technique at production sites

Forced evaporation sprinkling system is designed and installed at Evaporation Ponds of Production Facilities of MOL Pakistan to tackle the increasing production rates of produced water. In this system, produced water is evaporated forcefully through the specially designed sprinkler nozzles. Following is the brief summary of the Forced Evaporation system.
Produced water extracted/separated from Oil and Gas stream is collected through closed drain piping system in specially designed storage ponds widely known as Evaporation Ponds in Oil & Gas terminology. High Density Poly-Ethylene (HDPE) Liners are installed inside these Ponds to protect leakage or infiltration of produced water into underground fresh water reservoir. Thus, produced water is stored safely and securely and not allowed to contaminate the surrounding environment in any case. As, Produced water collected in these Ponds evaporates naturally through sunlight as per the fact that evaporation continues at all temperatures; thus, these are termed as Evaporation Ponds.
Centrifugal pumps installed at this Evaporation pond take suction from the produced water using suction piping of size 6 Inch at the depth of almost 6 Feet down the pond. Foot Valve is installed at the bottom of suction pipe to maintain positive head in the suction pipe and help prime the Centrifugal Pump as and when required during its operation.
Discharge of the pumps is connected to a common header of 6 Inch size which runs through the distance of 200 Feet along the Evaporation pond. It is to be noted that proper isolation and control valves have been installed on both the suction and discharge piping of the subject centrifugal pumps. Pressure gauges installed at discharge of these pumps indicate the pressure of the flowing produced water which is very useful in operation of the sprinkling system. Branch pipings of ½ Inch size have been taken off all along the 200 Feet main header to connect the specially designed sprinkler Nozzles to get the final output from the system. Length of theses branch pipings have been adjusted so that the sprinkled water mist drops back into the Evaporation pond to avoid contamination in the surrounding environment as per safety rules and regulations. Centrifugal pumps installed for the purpose are basically electric driven; so, proper control panel has been installed

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at site for effective control and running of these pumps. Proper data sheets have been compiled to calculate and record the performance of this sprinkling system on daily basis.

### 3.2. Design and development of Forced Evaporation system as per API RP-14E

Before the design and development of Forced Evaporation system for production sites at MOL Pakistan, natural evaporation was in place as the produced water production rate was quite low in the beginning of the company's operations. Produced water was stored in the specifically designed evaporation ponds located nearby the production facility with natural evaporation as the only source of disposal for the same. Daily rates for produced water were around 7 barrels per day which were easily evaporated naturally especially during the peak summers. However – with the passage of time – produced water production increased drastically to around 3000 barrels per day which was never manageable using natural evaporation. During this era, need for development of full-fledged Forced evaporation system was intensified; eventually resulting into the beginning of pilot project of Forced evaporation system at Makori Production Facility (MPF).
In the first phase of the project, necessary design calculations were aimed in accordance with pump of 180 GPM Flow rate. Following design calculations were performed mainly using the software to select the line size for discharge header for sprinkling purpose. In the appended software, necessary parameters were put in to get the desired line sizing against the Flow rate of 180 GPM which is equal to 6091 barrels per day.

Design basis for the subject software are the following two formulas:

**Erosional Velocity:**

$$V_e = \frac{C}{\sqrt{\rho_{mix}}}$$

$V_e$ = fluid erosional velocity, ft/sec
$C$ = erosional velocity co-efficient
$\rho_{mix}$ = liquid density, $lb_m/ft^3$

**Liquid Flow Velocity:**

$$V_l = \frac{.012\ Q_l}{d_i^2}$$

$V_l$ = average flow velocity of liquid, ft/sec
$Q_l$ = liquid flow rate, barrels/day
$d_i$ = pipe inside diameter, inches

Rule of thumb for the appended line sizing calculations is the fact that liquid velocity for any particular Flow rate in the pipeline should not be greater than the erosional velocity limit value of 14.98 ft/sec as mentioned in the appended table. For 6091 barrels per day of Flow rate, line sizing selected as 2 Inch pipeline for discharge header of Forced evaporation system is well under the Erosional velocity limit of 14.98 ft/sec. Thus, in the pilot phase of the project 2 Inch pipeline was fabricated and installed for Forced evaporation system at MPF. Mechanical valves, Strainers and other associated fittings were selected as per the 2 Inch pipeline as finalized in the design calculations.

**Table 8. Universal Line Sizing and Erosional Velocity Limit Calculator (API- RP 14E)**

| **Inputs** (Note: Please enter only values in front of √) | | | |
|---|---|---|---|
| **Stream Type** | **Liquid** | | |
| $D_{out}$ | Outer Diameter of Pipe (inches) | √ | **2.375** |
| $T_w$ | Pipe Wall Thickness (inches) | √ | **0.154** |
| $Q_l$ | Flow Rate at which flow velocity is required (bbl/day) | √ | **6091** |
| C | Erosional velocity co-efficient | √ | **100** |
| $\rho_{mix}$ | Density of Liquid ($lb_m/ft^3$) | √ | **44.54** |
| **Intermediate Formulas** | | | |
| $D_i$ | Inner Diameter of Pipe (inches) | **2.221** | |
| **Results** | | | |
| $V_l$ | Velocity of fluid flow in Pipe at given flow rate (ft/sec) | **14.82** | |
| $V_e$ | Erosional Velocity Limit (ft/sec) | **14.98** | |
| Has the existing velocity crossed Erosional velocity limit | | **No** | |
| $Q_{Max}$ | Maximum Allowable Flow Rate Considering Erosion, Noise and Corrosion (bbl/day) | **6166.05** | |

### 3.3. Performance Evaluation of pilot phase of Forced Evaporation system for Production site at MPF

Performance of the pilot phase of Forced Evaporation system was evaluated and found satisfactory with respect to the results attained using the system. Produced water was evaporated effectively using the sprinkling nozzles installed on the 2 Inch discharge Header downstream of centrifugal pump. 20 nozzles were installed on the discharge Header in such a way that evaporating mist fell inside the evaporation pond to avoid surface discharge of produced water. Average

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produced water evaporation recorded in a single day was 120 barrels per day which was quite good figure at that time when total produced water production rate was just 7 barrels per day. Thus, produced water generated each day from producing well was effectively disposed off on daily basis plus the extra volumes as well received from the Gurguri Gas Plant.

Following are the calculations for daily produced water evaporation rates achieved from the newly installed Forced Evaporation system at MPF.

**NATURAL EVAPORATION**

Natural Water evaporation from ponds can be calculated by the following relation

$$W = k.L^{a}.B^{b}.(Ps - P).(1+61.u^{0.85})$$

Where,

| | | |
|---|---|---|
| W | Water evaporated | Kg/sec |
| L | EP Length | m |
| B | EP Width | m |
| u | Wind speed | m/sec |
| Ps | Saturated vapour pressure in equilibrium state | |
| P | Actual vapour pressure (Pa) in the air | |

The k, a and b parameters in the equation are the measured data

| u, m/s | k | a | b |
|---|---|---|---|
| 0 – 1 | $3.72 \times 10^{-9}$ | 0.73 | 0.8 |
| 1 – 3 | $5.53 \times 10^{-9}$ | 0.77 | 1 |

Ps can be calculated as follows

$$Ps = 10^{5}. exp(13.67 - 5089/Tw)$$

Tw : Water temerature (K)

P value is defined as the following:

$$P = (H/100).10^{5}.exp(13.67 - 5098/Tg)$$

where,

$T_g$: Air temperature (K)

Figure 1: Natural Evaporation Rate Calculator

Calculator based on the above basic evaporation formula is as under:

**FORCED EVAPORATION RATE CALCULATOR (Makori-EPF)**

| Inputs | | |
|---|---|---|
| Wind Velocity | 2.3 | mile/hr |
| Water Temperature | 30 | °C |
| Air Temperature | 35 | °C |
| Relative Humidity | 38 | % |
| Density of Water | 1010 | Kg/m³ |
| **Dimensions of Sprinkled Mist** | | |
| | ft | m |
| Average Length of Mist (L) | 16.4 | 5.00 |
| Average Width of Mist (B) | 16.4 | 5.00 |
| **Intermediate Formulas** | | |
| Wind Velocity, u = | 1.028192214 | m/sec |
| Constant, if u<1 | 0.00000004363 | |
| Constant, if u>=1 | 0.00000009543 | |
| Surface Area of Mist | 24.98720164 | m² |
| Water Temperature | 303 | K |
| Air Temperature | 308 | K |
| Ps | 4263.5 | Pa |
| P | 2129.0 | Pa |
| Ps-P | 2134.5 | |
| $(Ps-P)*(1+61*u^{0.85})$ | 136453.8 | |
| **Results for single Sprinkle Nozzle** | | |
| Water Evaporated (W) | 0.01 | Kg/Sec |
| Water Evaporated (W) | 1.11 | m³/d |
| **Water Evaporated (W)** | **7** | **bbl/d** |

Figure 2: Forced Evaporation Calculator

Above calculations are for forced evaporation through single nozzle in operation during the whole 24 hours. Thus total evaporation rate for 20 nozzles for the whole day would be around 140 barrels per day.

### 3.4. Optimization and enhancement of Forced Evaporation system for Production sites

After the successful launch of the pilot phase of Forced evaporation system at MPF, it was decided to further optimize and enhance the Forced evaporation system for production sites of the company. Further procurement of pumps and mechanical pipings & fittings was carried out to fulfill the subject requirement. Four Pumps having 225 GPM Flow rate each were utilized this time for the purpose. Due to Erosional velocity limit constraint, pipeline of 2 Inch was not sufficient to handle the increased cumulative Flow rate of 30456 barrels per day. Thus, design calculations were revised as per the software; eventually leading to installation of 6 Inch discharge header instead of 2 Inch. Erosional velocity limit for new design calculations was 9.08 well under the maximum allowable limit i.e. 14.98 ft/sec.

Following are the necessary calculations conducted for 4 Pumps with 6 Inch discharge header for Forced evaporation system.

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| Table 9. Universal Line Sizing and Erosional Velocity Limit Calculator (API- RP 14E) | | | |
|---|---|---|---|
| Stream Type | Liquid | | |
| $D_{out}$ | Outer Diameter of Pipe (inches) | √ | 6.625 |
| $T_W$ | Pipe Wall Thickness (inches) | √ | 0.28 |
| Ql | Flow Rate at which flow velocity is required (bbl/day) | √ | 30456 |
| C | Erosional velocity co-efficient | √ | 100 |
| $\rho_{mix}$ | Density of Liquid ($lb_m/ft^3$) | √ | 44.54 |
| Intermediate Formulas | | | |
| $D_i$ | Inner Diameter of Pipe (inches) | | 6.345 |
| Results | | | |
| $V_l$ | Velocity of fluid flow in Pipe at given flow rate (ft/sec) | | 9.08 |
| $V_e$ | Erosional Velocity Limit (ft/sec) | | 14.98 |
| Has the existing velocity crossed erosional velocity limit | | | No |
| $Q_{Max}$ | Maximum Allowable Flow Rate Considering Erosion, Noise and Corrosion (bbl/day) | | 50323.78 |

### 3.5. Performance Evaluation of enhanced Forced Evaporation system for Production sites

As stated earlier, Forced Evaporation system was further enhanced to bigger canvas by utilizing 4 Pumps (225 GPM each) working simultaneously with 6 Inch discharge Header instead of 2 Inch as selected in the pilot phase of the project. Flow rate was enhanced as compared with the previous case; thus, number of sprinkling nozzles was increased to 60 instead of 20. These changes in design of the project boosted the effective area for sprinkler droplets eventually resulting into an increase in the produced water disposal rate.
Based on the new design parameters obtained from enhanced Forced Evaporation system, average produced water evaporation per day was recorded as high as 480 barrels per day which was 4 times more effective as compared with the previous case.

Calculator utilized for the estimate for the water evaporated in the 24 hours is already explained in the pilot case design.

### 4.1. Transformation from conventional produced water management techniques to Forced Evaporation system for Pakistani oil and gas companies

Produced water management techniques were evaluated in detail in the previous section for different oil and gas companies operating in the country including PEL, ENI, PPL, OGDCL, MOL, POL and MPCL. After thorough examination of the produced water data of the subject companies, it can be easily established that daily produced water production rates are below 4000 barrels per day for most of the companies. Keeping in view the fact that an efficient Forced Evaporation system can dispose off (5-8) barrels of produced water per sprinkling nozzle each day; system containing multiple such nozzles can definitely handle all of the produced water generated each day by the subject oil and gas companies. For instance, production facility generating 1250 barrels of water per day would roughly require installation of Forced Evaporation system (60 nozzles system) at 3 different evaporation ponds to tackle the whole day produced water production of that facility on the very same day. So, these companies currently relying on the conventional and relatively expensive means of produced water disposal should opt for comparatively cheaper mode of produced water management i.e. Forced Evaporation system. Taking advantage of the design calculations done for Forced Evaporation system for MOL production sites, oil and gas companies in the country may employ the same model as benchmark for inventing their models of same system at their production facilities. This gradual transformation from conventional disposal methods of produced water to Forced Evaporation system would have strong and positive economic impact as average cost for Forced Evaporation system is much cheaper than that for other conventional disposal techniques.

### 4.2. Economic impact of Forced Evaporation system in produced water handling

Forced Evaporation system has got major economic impact over other handling techniques of produced water in terms of huge cost savings as the former is much cheap method of produced water handling developed in these days. Average handling cost of produced water per barrel in Forced Evaporation system is around (0.1 – 1.0) USD which is much cheaper as compared with all other disposal means of produced water. Let's take example of Well Injection method which is widely used across the country as produced water management tool in various oil and gas companies. Average cost of produced water handling through Well Injection method is around (0.05 – 2.65) USD per barrel. Thus, oil fields generating thousands of barrel water of water each day consume huge amount of money in terms of produced water handling on daily basis. By switching from costly management option towards a cheaper option like Forced Evaporation system would definitely create huge economic impact on the monetary system of any company.

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Let's establish a comparison in terms of cost analysis for the oil and gas companies considered in this research project for the conventional as well as Forced Evaporation system for disposing produced water at each of their production facilities. This would help us generate various figures and graphs depicting the cost savings to be achieved by switching from conventional means towards Forced Evaporation system technique for produced water handling in various companies operating across the country.

### 4.3. Economic impact of Forced Evaporation system on MPCL

Mari Petroleum Company Limited (MPCL) is producing 905 bpd of water which is disposed off using Well Injection and Natural Evaporation at various operating fields in Sindh. Three of the five operating fields of MPCL i.e. Mari Petroleum Dharki, Mari Deep and Ghauri contribute 850 bpd in total which is disposed off using Well Injection method at the moment. By adopting Forced Evaporation at these fields would save USD 0.263 Million each year for the company as it is cheaper mode of disposal as compared with Well Injection method. As far as the Halini and Zarghoun fields are concerned, current methods of disposal i.e. Natural Evaporation system is the right option and the same should be continued both technically as well as economically.

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for MPCL.

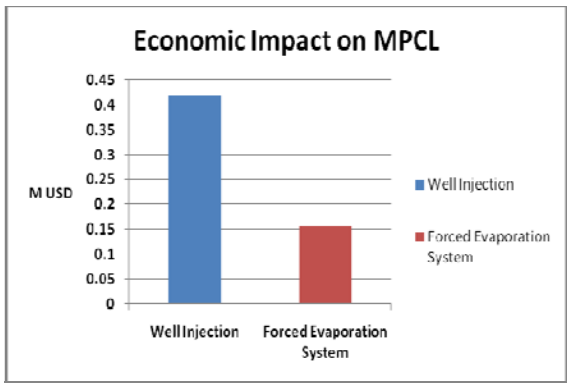


Figure 3: Economic Impact on MPCL

### 4.4. Economic impact of Forced Evaporation system on PPL

Pakistan Petroleum Limited (PPL) – one of the major operators of oil and gas fields across the country – is producing 2056 barrels of produced water on daily basis. Out of 2056 barrels, Mazrani and Hala Gas Fields are contributing 10 and 12 barrels per day each which are disposed off in Natural Evaporation method which is the most efficient means of produced water handling. So, there is no need to adopt Forced Evaporation system for these fields; however, remaining 2034 barrels of water contributed by Sui, Kandhkot and Aadhi gas fields need transformation from conventional Well Injection technique to Forced Evaporation system.

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for PPL.

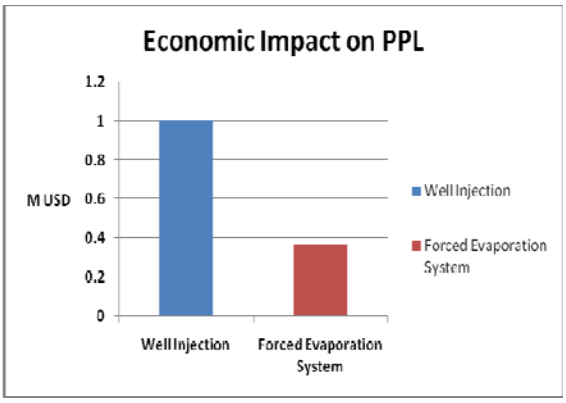


Figure 4: Economic Impact on PPL

Figure clearly depicts PPL would save 0.63 Million USD each year through effective implementation of Forced Evaporation System at Sui, Kandhkot & Aadhi Gas Fields. On the other hand, Mazrani and Hala Gas fields should continue with Natural Evaporation as current production rates of water are well under normal range.

### 4.5. Economic impact of Forced Evaporation system on OGDCL

Oil and Gas Development Company Limited (OGDCL) is operating multiple fields across the country; however, two producing wells are considered for analysis in the project. Total production of waste water from these two fields is around 2590 Barrels per day which is disposed off using well injection technique. As we know that well injection is a costly management mean for waste water disposal thus, considering forced evaporation system would save lots of money on daily basis for the company. OGDCL would save 0.801 Million USD each year using Forced Evaporation System. Well Injection would be considered in case of abrupt increase in water production in future

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for OGDCL.

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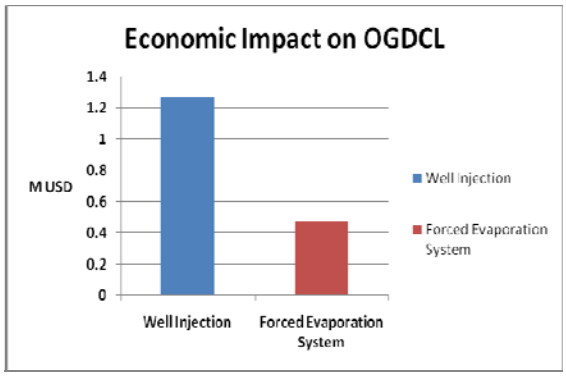

Figure 5: Economic Impact on OGDCL

### 4.6. Economic impact of Forced Evaporation system on ENI

ENI Pakistan operating in Sindh is the producer of around 600 barrels of produced water at the moment with well injection disposal method. Keeping in view the fact that produced water rates are well under controlled range, it is recommended to utilize forced evaporation system to tackle the waste water because it's much cheaper than the current mean of disposal. Transformation from Well Injection technique to Forced Evaporation can save ENI Pakistan 0.186 Million USD each year.

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for ENI Pakistan.

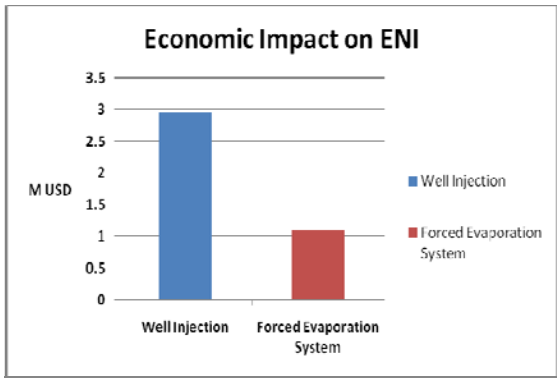

Figure 6: Economic Impact on ENI

### 4.7. Economic impact of Forced Evaporation system on PEL

Petroleum Exploration Limited (PEL) – one of the pioneer private sector operators of oil and gas in Pakistan– is generating 2500 barrels of produced water on daily basis from two fields. Currently, PEL is just storing the same in Evaporation Ponds without employing proper means for disposing it. Thus, the company needs to construct large number of Evaporation Ponds to store the produced water in theses ponds. Thus, implementation of Forced Evaporation system at PEL is the most appropriate and suitable option for disposing off the produced water and avoid construction of so many Evaporation Ponds for its storage.

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for PEL.

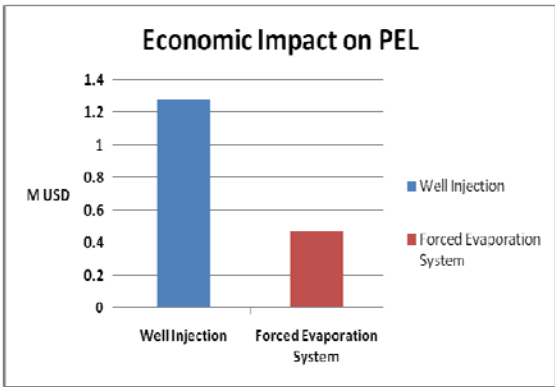

Figure 7: Economic Impact on PEL

Forced Evaporation System would help PEL save 0.81 Million USD each year. Natural Evaporation is suitable for Ghotki Badar Field.

### 4.8. Economic impact of Forced Evaporation system on POL

POL operates three fields having total produced water production as 8500 barrels per day. Waste water is managed through well injection method at all of these thee operating fields. Miyal and Khaur fields generate 3500 barrels of waste water which can be efficiently handled through forced evaporation system instead of current well injection system. However, Pindori field generating 5000 barrels per day of water is not recommended to go with forced evaporation system. Forced evaporation system is suitable for low water productions only as huge number of sprinkler systems would require huge manpower as well to maintain that system. Thus, POL should replace the current well injection system with forced evaporation system at Miyal and Khaur fields while Pindori field should continue with well injection method.

POL would save 1.086 Million USD each year through effective implementation of Forced Evaporation System at Miyal & Khaur Fields. For Pindori, current disposal method i.e. Well Injection is the most suitable option.

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Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for POL.

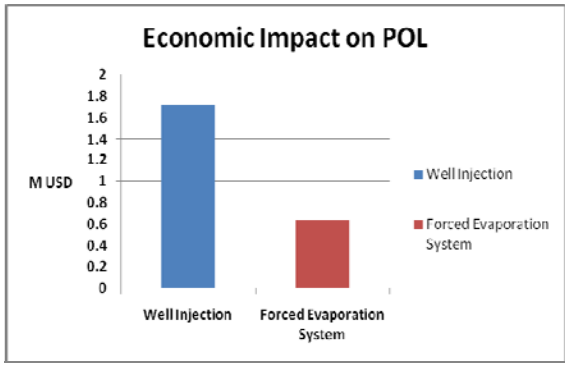


Figure 8: Economic Impact on POL

### 4.9. Economic impact of Forced Evaporation system on MOL

MOL Pakistan is operating four fields at the moment in district Karak of KPK. Aggregate waste water production is around 3850 barrels each day which is handled in evaporation ponds specifically designed for the purpose. Average cost of handling is 1.5 USD per barrel which accounts for construction of evaporation ponds, inter fields transportation etc. keeping in view the increasing trends of produced water, forced evaporation was designed and implemented at MOL Pakistan at all of the four fields of the company. MOL is saving 1.194 Million USD each year using Forced Evaporation System. Well Injection would be considered in case of abrupt increase in water production in future.

Following is the comparison of produced water handling in terms of cost per year using both of these disposal techniques for MOL.

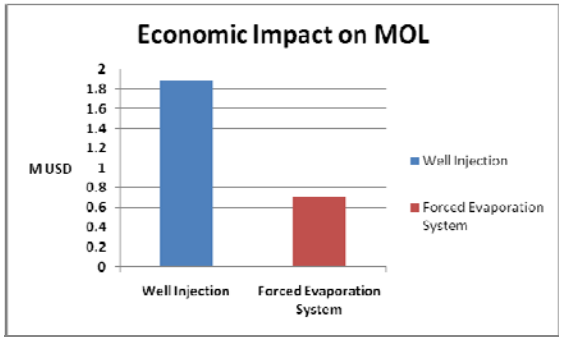


Figure 9: Economic Impact on MOL

MOL is saving 1.194 Million USD each year using Forced Evaporation System. Well Injection would be considered in case of abrupt increase in water production in future.

### 5.1. CONCLUSION

Keeping in view the produced water production rates in different oil and gas companies in Pakistan, Forced Evaporation system for produced water disposal is the most feasible and cheapest option among all the produced water management options available across the country. Companies operating in Pakistan can save millions of dollars by switching from conventional produced water handling techniques to Forced Evaporation system which is best for the production facilities generating daily produced water production rates in a controlled range under 4000 bpd. For higher produced water production rates, conventional produced water management techniques such as Well Injection are recommended because of higher water disposal capabilities. Furthermore, oil and gas fields generating under 30 bpd of produced water may opt for natural evaporation as disposal method because it is quite cheap and feasible mode for such controlled productions of produced water.

### 6.1. FUTURE RECOMMENDATIONS

Forced Evaporation system is developed and implemented in true spirit at production sites of MOL Pakistan which can be copied and opted at production sites of other oil and gas operators across Pakistan specially the sites generating controlled volumes of produced water each day (under 4000 bpd). Expertise and all other necessary support pertaining to the system would be provided to the operating companies ready to implement the subject system at their production sites.

Moreover, research work can be continued in future to include data for the remaining oil and gas companies operating across Pakistan to get clearer picture in terms of produced water handling in more efficient manner. Furthermore, future research work on the subject could be continued by taking into consideration the installation of produced water heaters to increase the temperature of the same; thus, further enhance average forced evaporation rate on every sprinkling nozzle. Besides the working on produced water heating mechanism, design of the sprinkler nozzles can further be optimized to help generate more fine mist and fog and thus more enhanced forced evaporation rates.

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