Modelling the Raw Water Demand of a Dry-Cooled, Coal-Fired Power Plant: A System Dynamics Approach

Author: Akashnie Raghu; Co-Author: Nalini Sooknanan Pillay

Eskom Research, Testing & Development

Private Bag 40175
Cleveland
2022

+ 27 11 629 5528/5436

RaghuA@eskom.co.za; PillayNa@eskom.co.za

ABSTRACT

South Africa is a country with limited and deteriorating quality of fresh water resources. Eskom, being the key supplier of electricity to the country, is the single, largest user of these precious water resources. Consequently, it is imperative that the organisation fully understands its long-term water supply and demand; with regards to quantity, accessibility and quality; for planning purposes to ensure that the security of water for electricity needs is met and to respond appropriately to the water crisis in South Africa. In modelling the long-term raw water demand, a system dynamics approach was favoured as a result of the ability to model, to an optimum level of complexity, the dynamic trends in water demand over life of the plant, without losing the ability to follow causality between system parameters with time delays. Water mass balances for a 4,800 MW dry-cooled, coal-fired power plant were constructed across every process utilizing water and, every water source and sink. Upon varying rainfall; coal quality; thermal efficiency; auxiliary power consumption; demineralized water recovery and consumption rates; third party water usage and, employing flue gas desulphurization technology and other water saving measures, efficient use of water at the plant to reduce raw water demand was simulated.

KEY WORDS

Water demand, fresh/raw water, system dynamics, power generation, coal-fired

1. INTRODUCTION

South Africa's limited fresh water resources and its deteriorating water quality pose challenges to Eskom (key supplier of electricity to the country) as it strives to secure national electricity supplies (Mike Muller 2009, CSIR 2010). Additionally, in a country of continuing economic growth, the electricity demand is increasing and consequently, the electricity infrastructure required to meet this demand will place further strain on these water resources (Vella 2012). It is, therefore, imperative for strategic planning purposes, to understand the dynamics and risk factors around the long-term supply-demand water paradigm, abridged by national water and environmental regulations and policies.

In modelling the long-term demand for water, it is notable that:

- Eskom is the single largest user of fresh water resources in the country (Govender 2009);
- Power generation by coal accounts for ~90% of its plant mix (Govender 2009);
- Water use for conventional wet cooling at these coal-fired power plants contributes ~80-90% of the total water use for power generation (Generation 2012);
- Dry cooling uses 15 times less water than conventional wet cooling (Pather 2000);
- New build coal-fired power plants may require wet Flue Gas Desulphurization (FGD) technology while existing plants may be retrofitted with FGD, adequately addressing emissions concerns but still increasing water demand (Govender 2009).

Initial modelling of Eskom's water demand began with a water balance across Medupi power plant (4,800 MW dry-cooled, coal-fired plant) (Eskom 2012), to understand and anticipate its raw water demand and the overall impact on the national integrated water grid. The dynamic behaviour of the water processes at the power plant were modelled with a 50 and 60 year plant life option using a system dynamics approach and STELLA® software.

The further advancement of the model to include water quality, quantity and water infrastructural aspects, resulted in a model that can be used by decision makers to engage in strategic dialogue and:

- to influence policy/legislation or the regulatory environment in securing future water resources and the enabling environment; and for
- scenario analyses to find leverage points for more efficient use of water at the power plant.

2. RESEARCH APPROACH

A system dynamics approach was used to calculate the raw water demand of Medupi power plant when varying performance parameters and, employing water saving measures and emission reduction technologies. The approach permitted an optimum level of detailed complexity to describe past and future dynamic trends in water demand over the life of the plant, without losing the ability to track causal linkages between system parameters with built-in time delays. Described below, are the steps undertaken in using this approach (Sterman 2000, Kirkwood 1998).

2.1. PROBLEM ARTICULATION

A literature survey was conducted to identify key variables (endogenous, exogenous and excluded variables) and to construct a model boundary chart (Table 1) in identifying the determinants affecting the water demand dynamics.

Table 1: Model boundary chart for water simulator

ENDOGENOUS VARIABLES	EXOGENOUS VARIABLES	EXCLUDED VARIABLES
Electricity production	GDP growth rate	Acid mine drainage
Eskom water supply & demand	Rainfall rate	Design specifications for new water infrastructure
Water source supply/yield & demand	Evaporation rate	
Electricity costs	Water quality	
Water saving measures	Sectoral water demand	
	Water tariffs	
	Coal quality	
	Water infrastructure capacities	

Water mass balances were constructed across every process utilizing water in the power plant and across every water source and sink; from the raw water reservoirs, through the electricity generation value chain, to the waste streams produced.

The model time horizon was determined by the plant life; this was taken to be 60 years, from the commissioning of the first unit (2013) to the decommissioning of the last unit (2073).

Reference modes were established and used as guidelines to compare to the raw water demand trends simulated.

2.2. DYNAMIC HYPOTHESIS

Before constructing a causal loop diagram with cause-effect relationships between key variables (Figure 1), an additional step to the modelling process was introduced. This step included the development of an integrated systems structure that provided a high-level map view of the sub-modules that would be developed. This step assisted in bridging the gap between the system dynamicists and the non-technical stakeholders so that key information was discussed on a common platform and included in the model.

With reference to the high-level causal loop diagram in Figure 1:

- Reinforcing loop **R1** illustrates that as the Gross Domestic Product (GDP) continues to grow due to the increasing economic growth in South Africa, the demand for electricity in the country increases. As a result of this increase in electricity demand, the generation capacity will also increase in order to meet this demand which in turn contributes to the growth and development in the country hence the knock-on effect on the GDP.

- However, the generation capacity and the choice of generation technology is limited by the availability of water for power generation and this is illustrated by balancing loop **B1**. As the electricity demand increases, the Eskom water demand increases since more water will be required for the production of electricity. An increase in water demand will result in a decrease in the amount of water that Eskom has available for power generation which in turn will limit/decrease the amount of electricity that the organisation can produce. As a result of not meeting the country's electricity requirements, the economic development in the country is affected and hence the GDP decreases.

- Similarly, balancing loop **B2** illustrates that as the GDP increases, all economic sectors flourish hence the competition for water resources increases. As the competition for water resources increases, the water available for use decreases which has a negative effect on Eskom's water availability. This decreased availability of water will limit/decrease the amount of electricity that the organisation can produce and the trend, as previously explained, is repeated.

- Additionally, water and energy-efficient technologies; emission-abatement technologies; water and energy tariffs; water restrictions and, water policies and government regulations/legislation will be explored to determine their effects on the water supply to and demand in Eskom and hence, on the country itself.

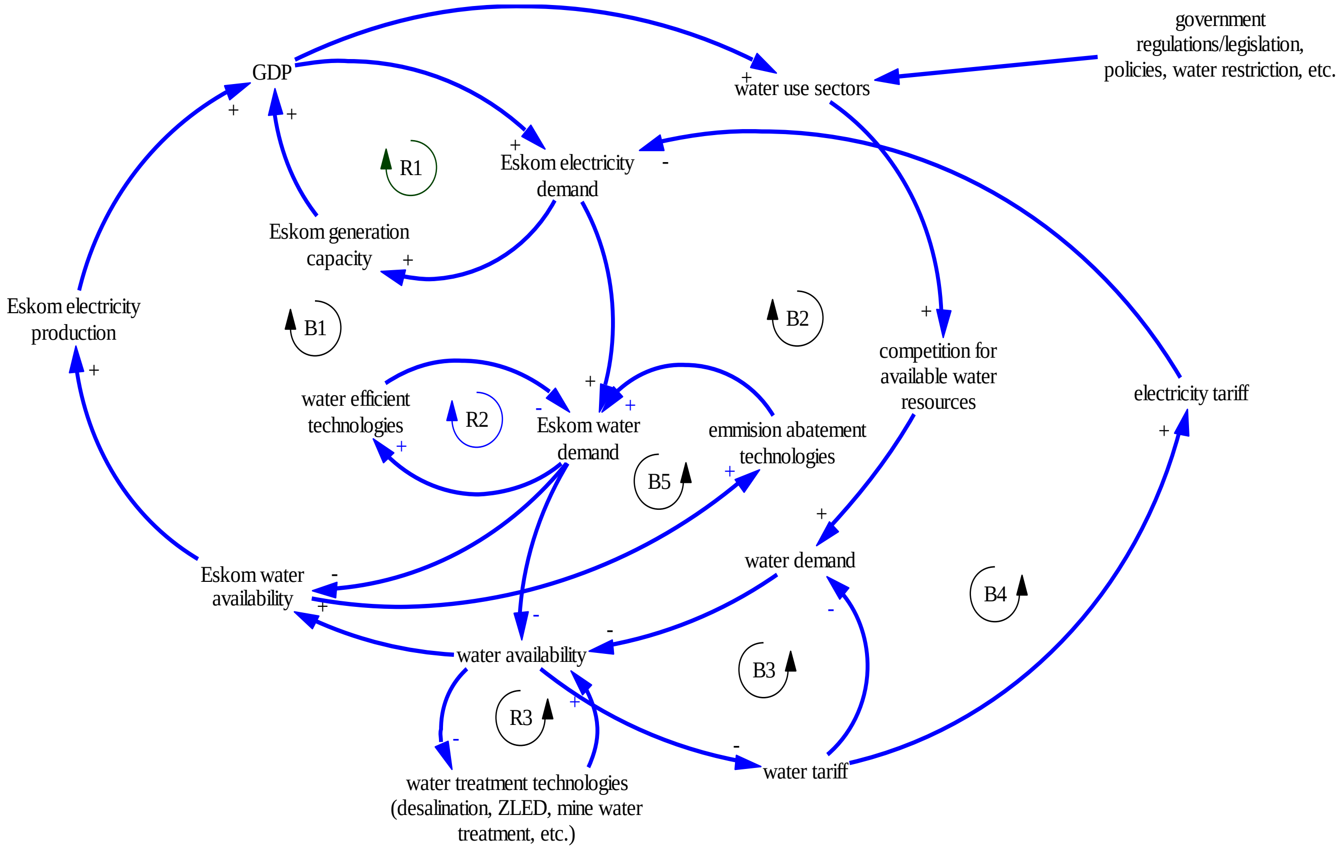

Figure 1: High-level causal loop diagram of water simulator

In order to perform a more detailed, quantitative analysis; the causal loop diagram was transformed into a stock and flow diagram using the system dynamics-based software, STELLA®.

2.3. SIMULATION MODEL

The structure of the model was specified by the following assumptions and general decision rules.

2.3.1. ASSUMPTIONS

- Sources of raw water included those from fresh water resources and rainfall only. Mine water recovery was not included.
- Quality of water met the specifications as stipulated in the Eskom chemistry standards (Hanekom 2008).
- All factors influencing the water mass balances except climatic conditions (rainfall and evaporation), number of units and station load factor remained constant throughout the life of plant. However, these

could still be varied within calibrated lower and upper user-defined limits.

- There was no accumulation of water within unit water processes.
- No mixing of process water streams occurred hence zero contamination or impurity ingress in process water streams.

It should also be noted that any reference to raw water demand is equivalent to the raw water from fresh water resources and does not include the raw water due to rainfall.

2.3.2. DECISION RULES

- Flows to/out of any processing unit, water source and water sink was governed by its respective physical and scientific laws.
- Every water mass balance was simply determined by the Law of Conservation of Mass (William L. Masterton 2009):

$$\boldsymbol{Accumulation = inflows - outflows + generation - consumption}$$

Equation 1

In addition to stating assumptions and establishing decision rules, parameters (constants) and initial conditions were also estimated..

The model structure developed for the water mass balance across the raw water reservoirs is illustrated in Figure 2.

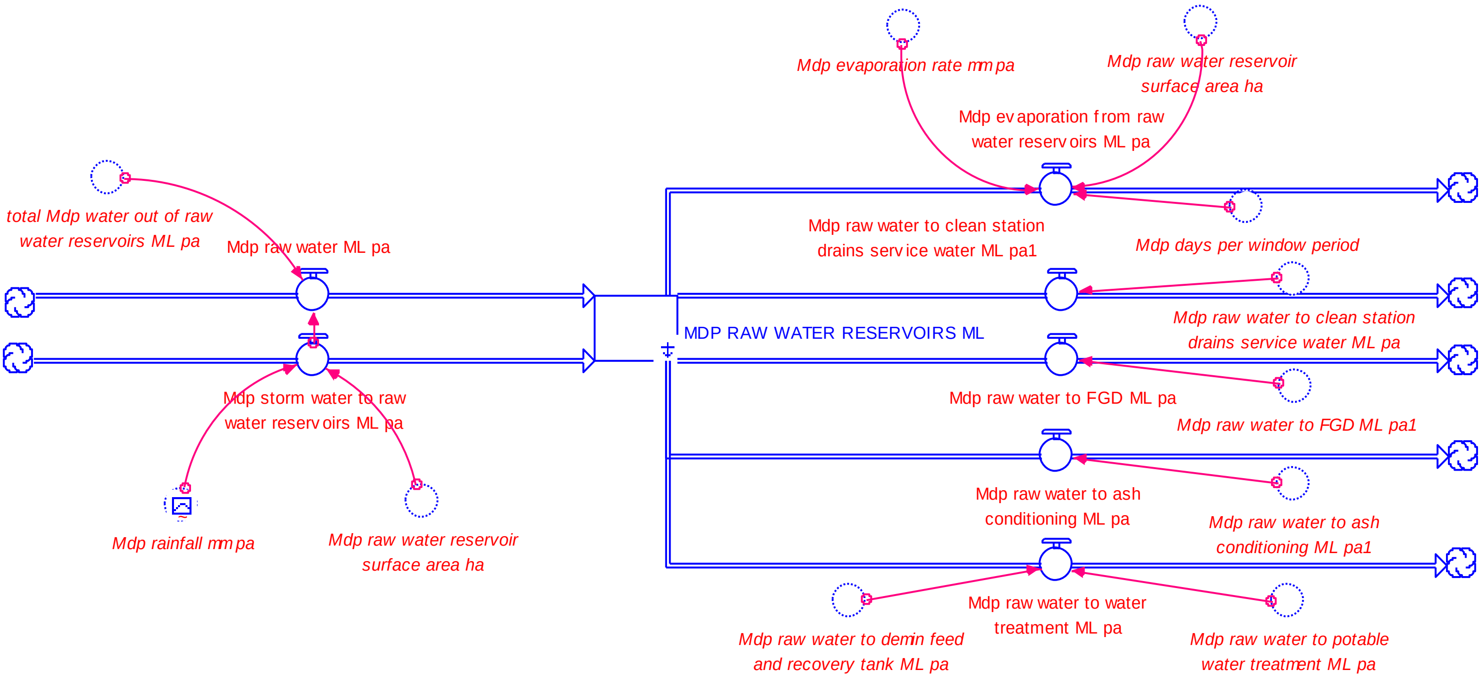

Figure 2: Water mass balance across raw water reservoirs

2.4. TESTING

Upon developing the model, runs were performed on selected scenarios and results obtained (given in Section 3) on the following parameters/variables only:

- Climatic conditions (rainfall)
- Thermal efficiency
- Auxiliary power consumption rate
- Demineralized water consumption rate per Unit Sent Out (USO)
- Demineralized water recovery rate
- Coal quality (calorific value, ash content, interstitial hold)
- Wet FGD (option of retrofitting FGD)
- Ash disposal (option of ash dump being operated by Eskom or the mine from which coal is supplied)
- Effluent disposal (option of effluent being disposed of in the ash dump or treated for water reuse)
- Sewage disposal (option of sewage being disposed of to the public stream or treated for water reuse)
- Third party use (supply of potable water to local mines and communities)

Upon testing, the model structure was reviewed to validate its consistency with purpose and boundary. Illustrations of the interfaces developed to perform scenarios are shown in the figures in APPENDIX A.

2.5. POLICY DESIGN AND EVALUATION

By performing sensitivity analyses on the above variables/parameters and options to simulate the dynamic trends in water consumption over the life of the plant, strategies/interventions that could be used to ensure the efficient use of water at the plant and hence reducing the raw water demand, was identified and are highlighted in Section 4.

3. RESULTS AND DISCUSSION

Upon testing the simulation model, the following results were obtained and discussions around these made.

3.1. IMPACT OF VARYING OPERATING PARAMETERS

In order to understand the effects of operating parameters on the raw water demand, it was important to conduct sensitivity analyses with a 10% upward or downward variation from the base case scenario to understand which factors had the most impact on an increase in the raw water demand and the strategies/interventions that, therefore, need to be considered. The results obtained in varying these parameters are tabulated in Table 2 and the effect of varying each parameter/variable (as indicated: 10% increase/decrease) on the raw water demand are discussed.

Table 2: Effect of varying parameters/variables on increasing raw water demand

PARAMETER	PARAMETER VARIATION [10% from base case]	EFFECT ON RAW WATER DEMAND [% increase from base case]
Rainfall	Decrease	4.10
Thermal efficiency	Decrease	2.40
Auxiliary power consumption rate	Increase	0.43[1]
Demineralized water consumption rate per energy unit sent out	Increase	1.46
Demineralized water recovery rate	Decrease	0.62
Calorific value of coal	Decrease	2.45
Ash content of coal	Increase	2.15
Interstitial hold of coal	Increase	0.61
Third party use	Increase of 100 ML pa	1.44

[1]Increase in specific unit water consumption per energy unit sent out

- Climatic conditions:
  As the mean annual rainfall decreased by 10%, the raw water demand increased by 4.1%. This can be attributed to the reduction in storm water accumulation in open water reservoirs, dams, ponds, etc. and surface water runoff which alleviate the raw water demand.

- Thermal efficiency:
  A decrease in the thermal efficiency of the plant by 10% resulted in a 2.4% increase in the raw water demand. Thermal efficiency of the plant determines the amount of coal required and hence the amount of ash produced. A lower thermal efficiency results in higher quantities of coal being required which in turn influences the higher quantities of ash being produced. As a result, the water required for ash conditioning (fly ash conditioning, bottom ash quenching and ash dump conditioning) increases (Elcock 2011).

- Auxiliary power consumption rate:
  A 10% increase in the auxiliary power consumption rate resulted in a 0.43% increase in the specific raw water consumption rate per energy unit sent out. This can be attributed to the lower quantity of energy units being sent out whereas the raw water demand remained fairly constant.

- Demineralised water consumption rate per energy unit sent out:
  As the demineralised water consumption rate per energy unit sent out increased by 10%, the raw water demand also increased by 1.46%. This can be attributed to the increased make-up water required by the demineralised water treatment plant to supply the demineralised water feed tank.

- Demineralised water recovery rate:
  By decreasing the amount of demineralised water that is recovered by 10%, the increase in raw water demand amounted to 0.62% as a result of more make-up water being required by the demineralised water treatment plant to supply the demineralised water feed tank.

- Coal quality:
  Using coal with a 10% lower calorific value resulted in a 2.45% increase in raw water demand. Similar to the thermal efficiency, the lower the calorific value, the higher the quantity of coal that is required. A higher quantity of coal in turn influences the ash that is produced and as a result, a higher quantity of water is required to condition this ash.

  The same rationale held true for a 10% increase in ash content of coal resulting in a 2.15% increase in raw water demand.

  Interstitial hold for water in coal also impacted on the water demand. As this increased by 10%, raw water demand increased by 0.61% as a result of more water being absorbed in the interstitial cavities of the bottom ash during quenching.

- Third party use:
  The option of supplying 100 ML pa of potable water to third party users (mine, local communities, etc.) resulted in a 1.44% increase in the raw water demand.

The parameters that increased raw water demand in descending order are given below:

- Rainfall (4.1%)
- Calorific value of coal (2.45%)
- Thermal efficiency (2.4%)
- Ash content of coal (2.15%)
- Demineralized water consumption rate per energy unit sent out (1.46%)
- Third party water use (1.44%)
- Demineralized water recovery rate (0.62%)
- Interstitial hold of coal (0.61%)

By analysing the above, the following are essential:

- Locality of the power plant and its associated climatic conditions for choice of operating conditions (wet versus dry technologies) of the power plant with regards to water use (extensive or not).
- High coal quality.
- Maximum cooling in the condenser.
- Proactive power plant maintenance and effective process control and monitoring.
- Negotiations of third party water use.

3.2. WATER SAVING MEASURES

In addition to the above parameters, water saving measures (operation of the ash dump and, effluent and sewage disposal) to ensure the efficient use of water in the power plant was considered. The effects of these water saving measures on raw water demand are tabulated in Table 3.

Table 3: Effect of water saving measures on raw water demand

SAVING MEASURE/ TECHNOLOGY	OPTION	EFFECT ON RAW WATER DEMAND [% water savings]
Ash disposal	Ash dump operated by mine	4.35
Effluent disposal	Effluent sent to ash dump	0.14
Sewage disposal	Sewage recovered	6.78

Given below are the water savings achieved in descending order:

- Sewage recovered (6.78%)
- Ash disposal operated by the mine (4.35%)
- Effluent sent to the ash dump (0.14)

Reasons for the above options resulting in water savings are described below:

- Sewage disposal:
  The effect of recycling sewage as opposed to disposing of it to the public stream resulted in a 6.78% decrease in the raw water demand. This can be attributed to the reuse of water that was recovered from treating the sewage. However, it must be noted that treatment of these streams are energy-intensive and the impacts of the water treatment required on auxiliary power consumption was not considered.

- Ash disposal:
  Ash disposal operated by the mine (not within the power plant boundary) from which coal was supplied as opposed to being operated by the power plant resulted in a 4.35% decrease in the raw water demand. This was as a result of no water being required for conditioning of the ash dump.

- Effluent disposal:
  As a result of the effluent being disposed of to the ash dump as opposed to being treated in an evaporator, the raw water demand decreased by 0.14%. This can be attributed to alleviating the raw water demand that was required for ash conditioning.

3.3. IMPACT OF WET FGD TECHNNOLOGY

Wet FGD technology was considered to determine the additional quantity of raw water required since water is used to scrub off the flue gases to reduce SO_x emissions (Carpenter 2012). Employing FGD resulted in a 91.2% increase in raw water demand as tabulated in Table 4 and illustrated in Figure 3. This technology is an important consideration in the model since it not only impacts water security but has a resultant financial impact.

Table 4: Effect of wet FGD on raw water demand

SCENARIO	DESCRIPTION	EFFECT ON RAW WATER DEMAND [% increase from base case]
1	Base case (No FGD)	
2	FGD fitted	91.2[2]

[2]Assumptions: FGD effluent per GWh = 70 m^3 per GWh
FGD evaporation rate per GWh = 70 m^3 per GWh

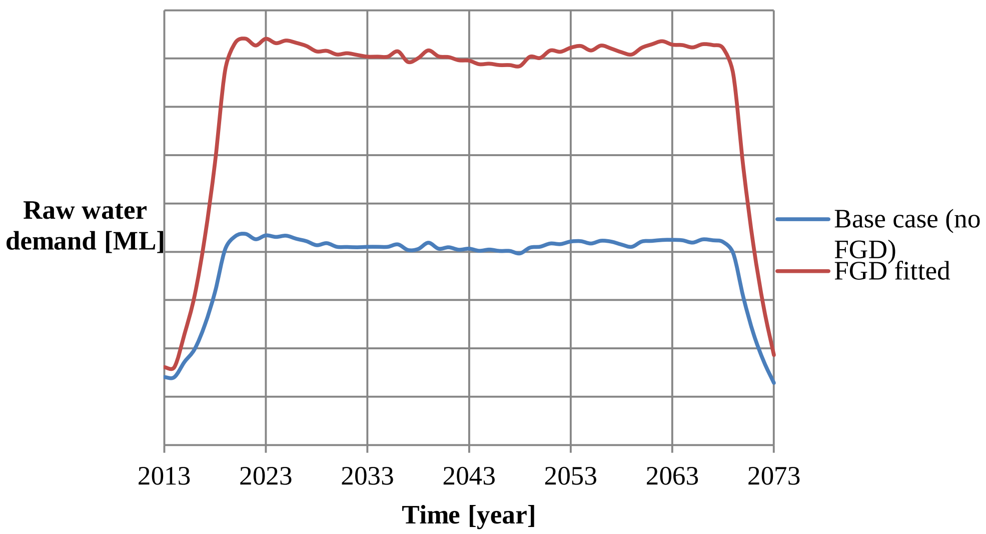

Figure 3: Effect of FGD on raw water demand

3.4. SCENARIO ANALYSES

In summarising the effects of each parameter considered and the options of saving measures, scenarios were developed to understand the combined impacts thereof on raw water demand. The scenarios are described below with their respective effects on raw water demand (compared to base case) tabulated in Table 5 and illustrated in Figure 4:

- Scenario 1: Base case (used for comparison)
- Scenario 2: No saving measures
- Scenario 3: Saving measures
- Scenario 4: Parameters varied accordingly to increase raw water demand
- Scenario 5: Parameters varied accordingly to reduce raw water demand
- Scenario 6: Worst case: No saving measures + parameters varied accordingly to increase raw water demand
- Scenario 7: Best case: Saving measures + parameters varied accordingly to reduce raw water demand

Table 5: Scenario analyses on raw water demand

SCENARIO	DESCRIPTION	EFFECT ON RAW WATER DEMAND [% increase from base case]
1	Base case	
2	No saving measures	6.8
3	Saving measures	-4.4[2]
4	Parameters varied accordingly to increase raw water demand	12.2
5	Parameters varied accordingly to reduce raw water demand	-8.0[2]
6	Worst case: No saving measures + parameters varied accordingly to increase raw water demand	20.5
7	Best case: Saving measures + parameters varied accordingly to reduce raw water demand	-9.1[3]

[3]Negative signs indicated % decrease from base case

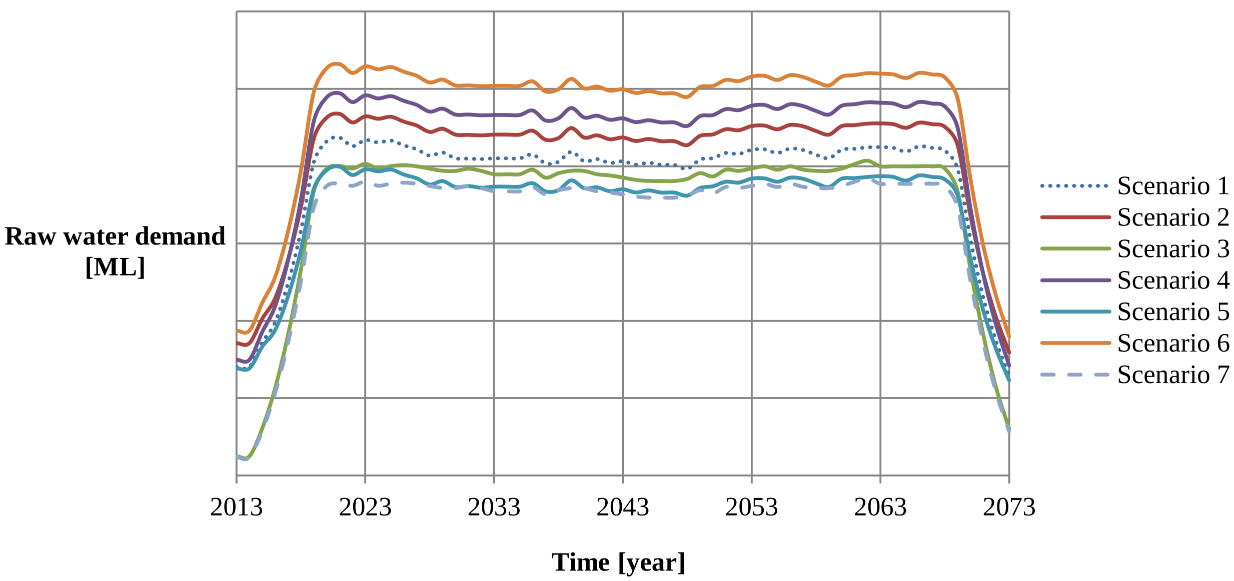

Figure 4: Raw water demand profile for scenarios

By analysing the above, the parameters that were varied to reduce raw water demand resulted in higher savings (8% water saving) than only employing the saving measures (4.4% water saving). Obviously, the combined effect resulted in a larger water saving of 9.1%.

Similarly, by varying the parameters that increased raw water demand resulted in a 12.2% increase. This increase was higher than not employing any saving measures (6.8%). The combined effect of these resulted in a 20.5% increase in raw water demand.

It can, therefore, be stated that although saving measures will reduce the raw water demand, the impact of operating conditions within the plant and the quality of resources will reduce the raw water demand significantly.

It must be noted that in addition to the factors considered, many other sensitivity analyses and hence, additional scenarios, can be run to understand the behaviour of raw water demand over the life of the plant.

4. CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and recommendations were made to ensure efficient use of water in the plant to reduce the raw water demand:

- In high precipitation areas, accumulation of storm water and surface water runoff alleviate the demand of raw water hence geographical location and its associated climatic conditions are important factors in the choice of operating technologies (water intensive or not) of a coal-fired power plant.

- Maintaining a high thermal efficiency will aid in reducing the raw water demand since less coal would be required to achieve the same heat energy needed. Less ash will, therefore, be produced resulting in less water being required for fly ash conditioning, quenching of the bottom ash and ash dump conditioning.

  Thermal efficiency may be increased by increasing the operating steam parameters (temperature and pressure: supercritical) and using more efficient coal-fired technologies such as cogeneration, integrated gasification combined cycle and direct firing of gas turbines with coal for new power plants. For existing power plants, the operating thermal efficiency may be increased to its design thermal efficiency by proactive power plant maintenance; continuous, effective monitoring; replacing existing inefficient plants to make them more efficient; installing and monitoring process controls and instrumentation and, coal drying (Elcock 2011).

- Considering less energy-intensive processes for water and waste treatment, such as freeze thaw treatment as opposed to reverse osmosis, will aid in a higher amount of energy units sent out hence reducing the specific unit water consumption per energy unit sent out (Smith 2003).

- Reducing the demineralized water consumption rate per energy unit sent out and increasing its recovery rate by ensuring effective water treatment of demineralized water prior to being fed to the boiler and enhancing heat transfer (maximum cooling) in the condenser respectively, will reduce the amount of make-up water to the demineralized treatment plant hence reducing the raw water demand.

- Coal with a higher caloric value, lower ash content and lower interstitial hold for water will be preferable as a result of less ash being produced and therefore, reducing the raw water required for ash conditioning (fly ash, bottom ash and ash dump conditioning). However, this has to be weighed against the coal price dynamics and cost of primary energy.

- Employing wet FGD technology will always increase the raw water demand; however, water use can be reduced by recovering evaporative losses from the wet scrubbers. Dry scrubbing units which eliminate the use of water may also be used; however, the removal efficiencies of SO_x are lower (Elcock 2011, Carpenter 2012).

- The choice of having the ash dump being operated by the power plant will result in an increase in water demand as a result of the raw water being needed for ash conditioning. However, mine water recovery and effluent streams (depending on its quality) can be considered in this regard to help alleviate the raw water demand to some extent.

- Treating effluent and sewage and reusing the water recovered will reduce the amount of raw water required directly. However, the treatment processes required may be energy-intensive and indirectly contributing to the higher raw water demand that may be required for the increased auxiliary power consumption. Therefore, auxiliary power consumption for water treatment processes should be further investigated to look at the integrated system and the impact thereof on raw water demand.

- Supplying potable water to third party users (mine, local communities, etc.) will inherently increase the raw water demand and community obligations weighed against the cost of increased demand for water if third party users have to be serviced.

Additionally, the following need to be considered:

- Water chemistry associated with water quality for raw, cooling, ash, seepage and station drains water to determine its impact on raw water demand. These dynamics will be further explored during the continuation of the model.

- Unforeseen/undesirable events that will increase the water demand and/or result in ingress of impurities from one water stream to another. In current operating conditions at power stations, leakages do arise (pipe bursts), streams do come into contact with each other resulting in impurity ingress (cooling water contaminating the steam as a result of condenser tube leaks), etc. and the effect of these will increase the raw water demand and may even affect the water treatment required.

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- Research and simulator development participants: Barry MacColl, Chris Gross, Nandha Govender, Alwyn van der Merwe, Motshewa Motimolane, Bonginkosi Nyembe, Primary Energy Division (Water and Environment), Group Technology (Process Engineering Integration Coal), Dr. Willem Nel.

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APPENDIX A

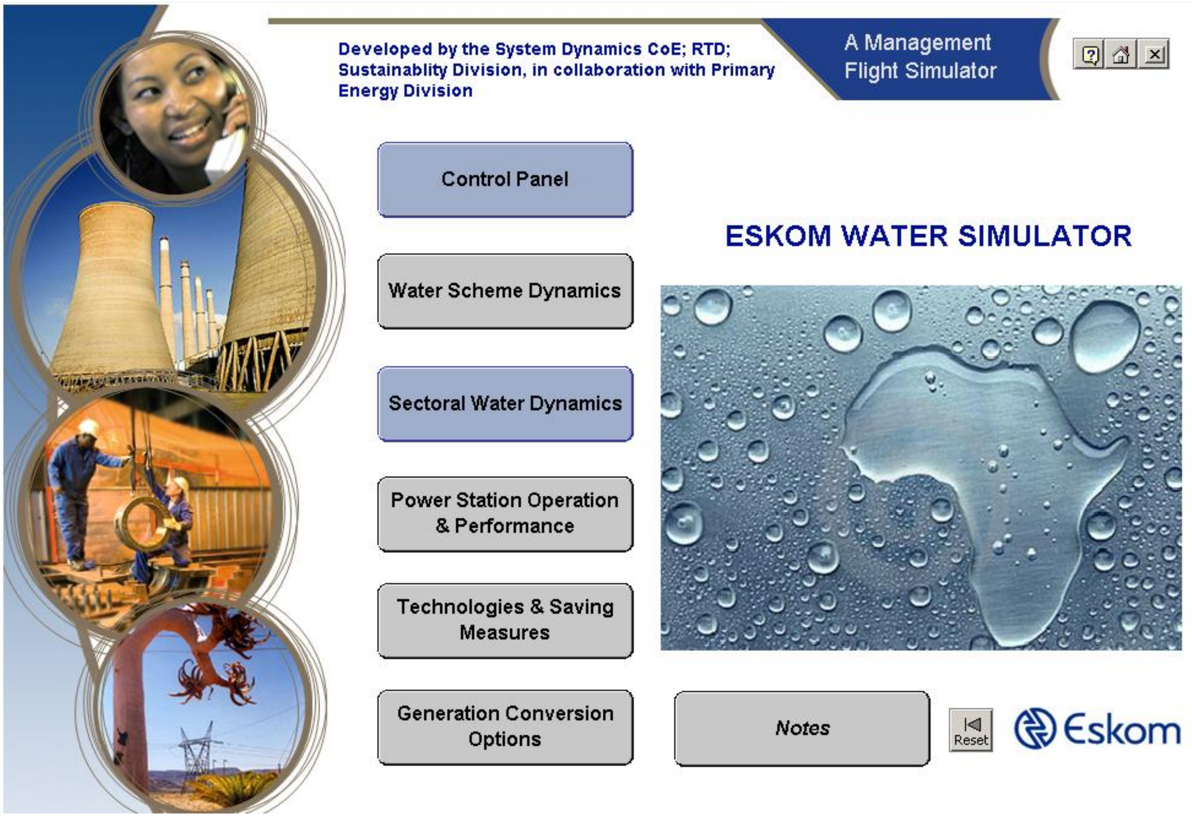

Figure 5: Interface 1

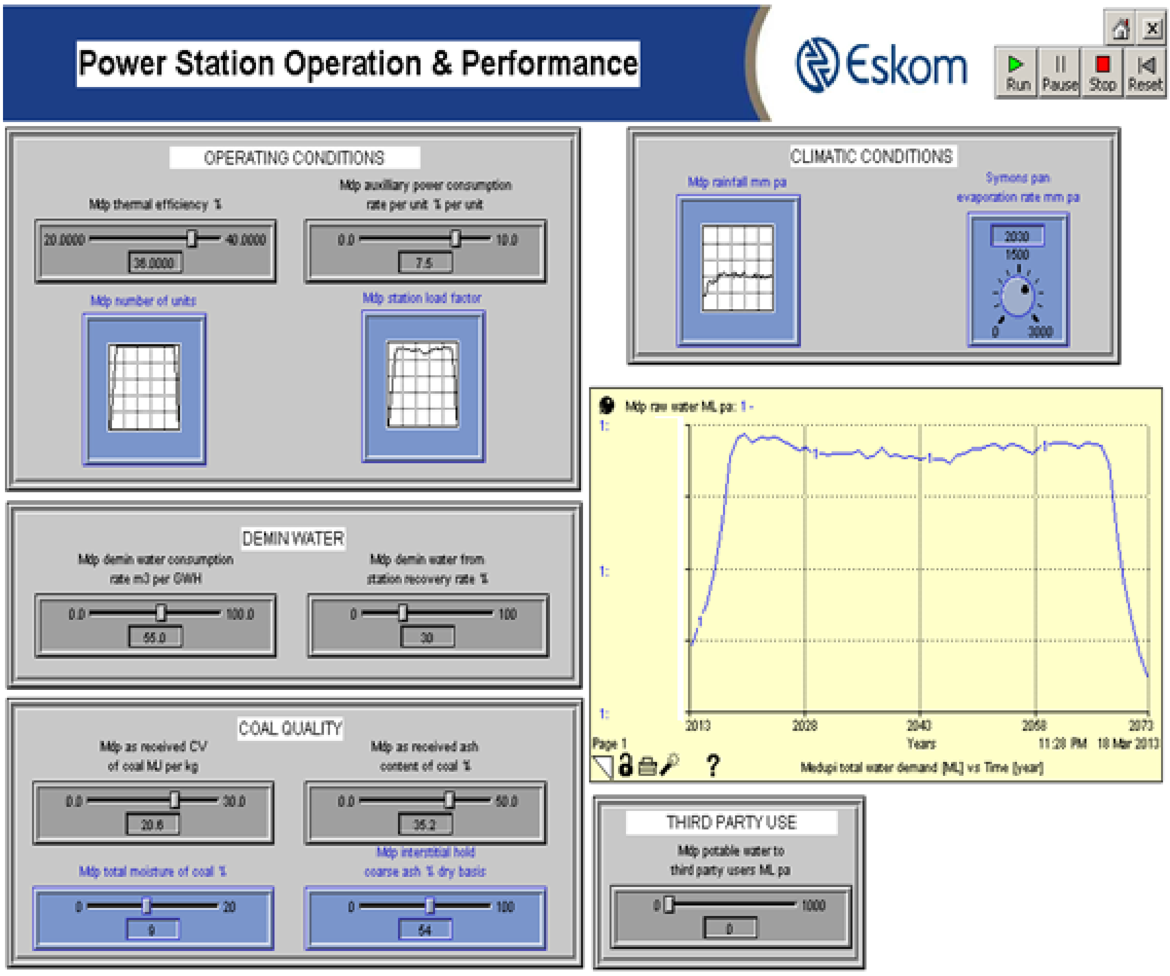

Figure 6: Interface 2

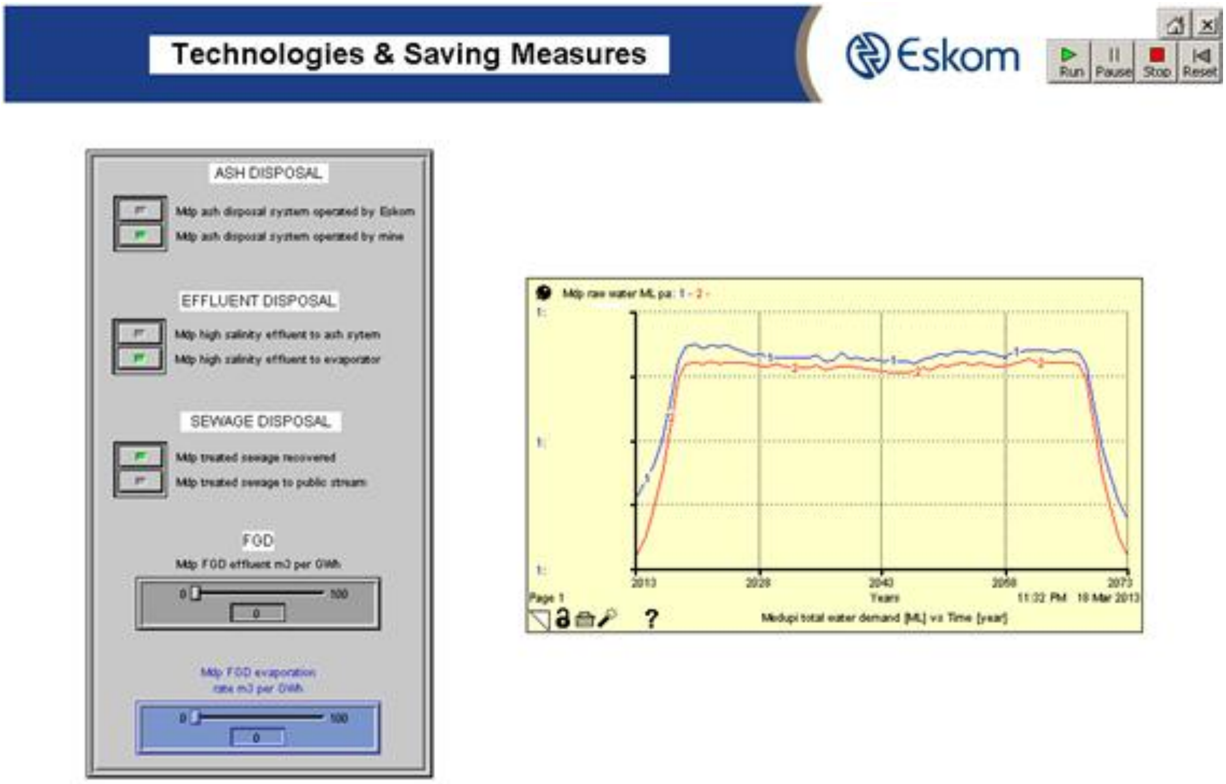

Figure 7: Interface 3