A methodology for implementing a water balance of ESKOM power stations using the online condition monitoring software EtaPRO

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Abstract

Eskom produces approximately 90% of the electricity used in South Africa of which approximately 90.8% is from fossil fuel power plants. The process of electricity generation requires a significant quantity of raw water; therefore, Eskom is considered a strategic water user in South Africa. Water management is a growing focus area due to the increase in water usage and requires continuous improvement. Water management has been identified as an area lagging behind on the advanced analytics initiatives in Eskom.

Excel based tools were used for the development of water balance models and water performance calculations in Eskom. This was attributed to the user-friendly functionality and availability to all users. However, the Excel tool posed challenges in allowing for standardisation and validation of calculations, tracking of model changes, continuous trending and storage of data as well as structured graphical user interfaces for screens and dashboard developments.

There was therefore a need to develop a methodology on how to structure a water balance model for coal-fired power plants with standard calculation templates that allowed for customisation by each power plant within Eskom. It was required that the water balance model be implemented on a performance and monitoring tool allowing for comparison of power plant targets to actual online data in real time, enhancing the monitoring capabilities. It should have the ability to generate real time water performance data creating an opportunity for improved water management across the generation fleet.

The approach adopted in this dissertation was to learn from existing Eskom Excel water balance tools and develop a standard mathematical model in the form of EtaPRO calculation templates. These templates are be structured such that they function as process components to develop water balances at power plants. The mathematical verification of the Excel calculations were to be conducted using Mathcad. The access to real time data, performance monitoring capabilities and availability at all Eskom Power plants, led to the selection of EtaPRO as the modelling platform.

The research conducted led to the development of a methodology for setting up a water balance model for a wet-cooled coal-fired power plant. Calculation templates developed into EtaPRO were validated against the Mathcad mathematical model. The results included a well-documented mathematical model of a water balance in Mathcad and the development of 19 calculation templates that perform the function of standard process components. In addition to calculation templates, multiple Non Volatile (NV) records were created to allow the power plants to capture and track permanent data inputs. NV records also allow for creation of case studies, improving the process monitoring capabilities. A water balance model for a selected power plant was simulated in

EtaPRO using the developed calculation templates and user defined formulae. Test screens and dashboards were created to illustrate how the calculation templates and water balance framework would be used to develop a typical water balance model and monitoring system.

In conclusion, it is possible to develop process models within the EtaPRO software from well-defined mathematical models to address the performance monitoring concerns on water systems within Eskom.

Declaration

I, Preetha Sewlall, hereby declare the work contained in this dissertation to be my own. All information which has been gained from various journal articles, text books or other sources has been referenced accordingly. I have not allowed, and will not allow, anyone to copy my work with the intention of passing it off as their own work or part thereof. I know the meaning of plagiarism and declare that all the work in the document, except for that which is properly acknowledged, is my own. This thesis/dissertation has been submitted to Turnitin module and I confirm that my supervisor has seen my report and any concerns revealed by such have been resolved with my supervisor.

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List of Nomenclature

General symbols

A	Surface Area of dams and ponds (ha)
C	Concentration of chemical species in water (ppm)
c_p	Specific heat of water (kJ / kg.°C)
C_s	Primary sludge concentration (%)
CV	Calorific Value of coal(As Received) (MJ/kg)
e	Evaporation intensity (m/s)
E	Cumulative energy output (GWh)
f	Factor / fraction
i	Rainfall intensity (m/s)
h_{fg}	Change of phase enthalpy (kJ / kg)
I	Water performance (L/kWh)
L_f	Load factor
LHV	Lower heating value (kJ/kg)
m	Mass of solids (tons)
$\dot{m}$	Mass flowrate (kg/s)
N	Cycles of Concentration
n	Number
R	Ratio
Δs	Change in storage within the selected hydrological unit
t	Time period (day)
T	Temperature(°C)
U	Usage of potable water per capita (m^3/capita)
v	Volume of water (Ml)
$\dot{v}$	Volume flowrate of water (m^3/h)
$\dot{W}$	Work generated by a steam turbine (GW)
X	Mass fraction of coarse or fly ash

Greek symbols

η	Efficiency (%)
ρ	Density (kg/m^3)
Δ	Change in storage

Subscripts

a	Actual condition
abs	Ash absorption
AIH	Ash Initial Hold
aux	Auxiliary
BD	Clarifier blow down
bw	Backwash
cap	Demin vessel capacity
cl	Clarifier
cf	Correction factor
cpp	Condensate Polishing Plant
csy	Coal Stock Yard
CT	Cooling tower
CW	Cooling water
d	Design condition
D	Cooling tower drift and windage losses
dem	Demin water
ds	Dust suppression
E	Evaporation
eff	Effluent from the water treatment processes
emp	Employees
$evap$	Evaporation
M	Cooling water make-up stream
Pan	Pan factor
p	Potable water
q	Quenching
r	Run-off
$regen$	Demin and CPP regeneration
s	Solids
ss	Suspended solids
st	Station
sso	Station sent out
th	Thermal
w	Water

Acronyms and Abbreviations

AIH	Ash Interstitial Hold
BFP	Boiler Feed Pump
CCW	Circulating Cooling Water
COC	Cycles of Concentration
CPP	Condensate Polishing Plant
CSY	Coal Stock Yard
CV	Calorific Value
CW	Cooling water
DCDA	Dry-cooled and dry-ash
DCWA	Dry-cooled and wet-ash systems
Demin	Demineralised
EPRI	Electric Power Research Institute
GUI	Graphical User Interface
HP	High Pressure
ID	Identification
IEA	International Energy Agency
IX	Ion Exchange
LAN	Local area network
LP	Low Pressure
MCR	Maximum Capacity Rating
MB	Mass Balance
MILP	Mixed integer linear programs
MINLP	Mixed integer non-linear programs
NHR	Nett Heat Rate
NIST	National Institute of Standards and Technology
NV	Non Volatile
PF	Pulverised Fuel
ppm	Parts per million
SQL	Structured Query Language
STEP	Station Thermal Efficiency Performance
TCHR	Turbine Cycle Heat Rate
TSS	Total Suspended Solids
UDF	User Defined Formulas
SSO	Station Sent Out
UI	User Interface
WAN	Wide area network
WCDA	Wet-cooled and dry-ash systems
WCWA	Wet-cooled and wet-ash
WTP	Water Treatment Plant
WUL	Water User Licence

ZLD	Zero Liquid Discharge

1. Introduction

1.1 Background of study

Power generation has been internationally recognised as an industry with a significant environmental footprint of which water use efficiency is a key aspect [1]. Water security has become a worldwide concern, especially in the power generation industry. It is therefore under increasing pressure to conserve water [2]. The increase in demand for energy and water can be attributed to population and economic growth [2]. The water demand between the year 2000 and 2050 is estimated to grow by 55% worldwide [2]. This is mainly due to the increase in manufacturing, thermal power generation, and domestic use. According to the International Energy Agency (IEA) New Policies Scenario, water consumption could increase by almost 40% by 2050 [2].

Eskom produces approximately 90% of the electricity used in South Africa, of which approximately 90.8% is from coal-fired power plants [3]. The process of power generation results in Eskom utilising approximately 2% of the country's total water consumption annually [3]. Water consumption is referred to as water that is withdrawn from a source and not returned to the same source [4]. South Africa is ranked as the 30th driest country in the world and is labelled as a semi-arid country [5]. As a result Eskom is regarded as a strategic water user [6]. Eskom’s water security is under threat due to the increase in water usage trends beyond that of the available catchment capacity [3]. Thus, water management in Eskom has become a growing focus area requiring continuous improvement.

Eskom has developed a water strategy aimed at addressing environmental sustainability by achieving full environmental compliance in order to reduce legal contraventions and enhance operational sustainability.

Eskom operates thirteen coal-fired power plants across South Africa with a total generating capacity of 36288 MW. Coal, currently used as the primary source of chemical energy, is converted into thermal energy within the boiler in the form of super-heated steam. The super-heated steam is converted into mechanical energy via turbines, and then finally converted into electrical energy by the generator. Due to efficiency losses and the inability to convert all the heat input from fuel into electricity, energy is dissipated into the environment. Most power plants dissipate this waste heat via cooling systems [7]. For wet-cooled power plants, cooling water (CW) is used as the cooling medium [8]. Figure 1 illustrates the water reticulation system typical for a wet-cooled coal-fired power plant configuration.

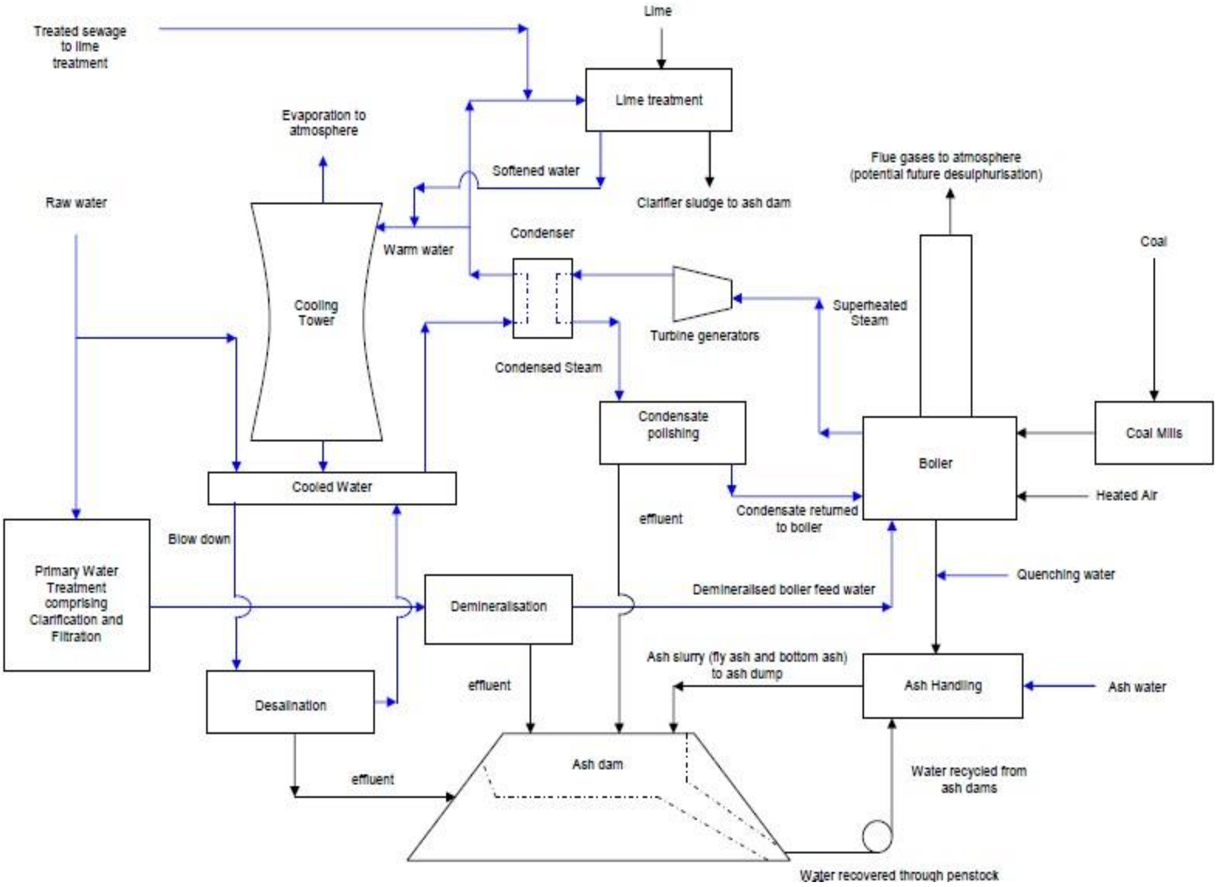


Figure 1: Typical water cycle of a wet-cooled and wet-ash coal-fired power plant [1]

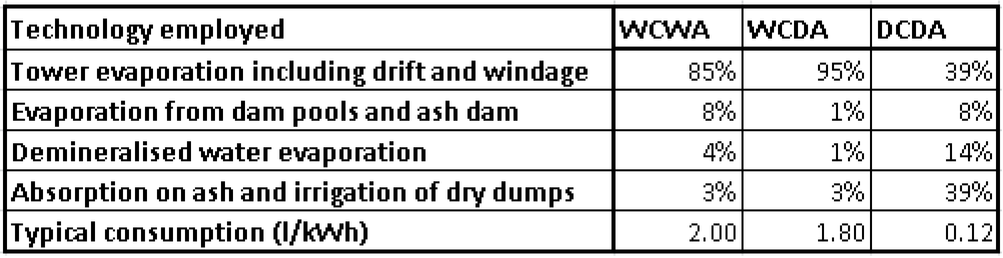
There is a distinct correlation between the varying technologies used at power plants and water consumption [7]. This is mainly evident for CW systems and ash plants. Power plants are usually categorised into:

- wet-cooled and wet-ash (WCWA) systems
- dry-cooled and dry-ash (DCDA) systems
- wet-cooled and dry-ash systems (WCDA)
- dry-cooled and wet-ash systems (DCWA)

Eskom currently operates WCWA systems and DCDA systems. The water use efficiency varies between the different technologies, with dry-cooled systems showing a reduced water footprint as compared to that of wet-cooled technologies [8]. It is estimated that between 85% to 95% of the total water requirements in a thermal power plant are for cooling purposes [9]. As a result more focus is applied to wet-cooled power plants when it comes to improving water consumption performance within Eskom.

The other water consumers are divided into demineralised (Demin) water, potable water, and ash handling water requirements [10]. Power plants use a water performance indicator, which is the raw water consumed per station sent out energy, to assess water performance. The water performance ranges between a value of 1.7L/kWh to 8L/kWh for WC power plants depending on plant configuration and technologies employed [11]. Table 1 illustrates typical water performance figures for various technologies used within Eskom power plants.

Table 1: Water performance for various power generation technologies [12]



Technology employed	WCWA	WCDA	DCDA
Tower evaporation including drift and windage	85%	95%	39%
Evaporation from dam pools and ash dam	8%	1%	8%
Demineralised water evaporation	4%	1%	14%
Absorption on ash and irrigation of dry dumps	3%	3%	39%
Typical consumption (l/kWh)	2.00	1.80	0.12

Eskom is required to set annual water performance targets for each power plant in order to manage the raw water consumption from the various water catchments. These targets are based on water models developed within Eskom. Over the years, power plants have struggled to meet allocated water performance targets for various reasons. Stricter environmental legislations imposed on Eskom by the Regulator has also resulted in greater pressure on Eskom to ensure compliance [13].

Water management at Eskom requires better understanding through further research into the processes defining the water balance model and the development of water management tools. Water balance models are the most widely used tool to understand the water consumption challenges experienced at power plants. Eskom is faced with limited knowledge into what the water management constraints are. This is mainly due to insufficient water flow metering and unavailability of water management resources available to provide quantification of unmeasured water streams. As a result, water leaks and misuse of water are often over-looked due to the inability to identify and quantify these losses. A water minimisation study was conducted on an Eskom power plant [14]. One of the findings was that proactive identification and maintenance of any leaking equipment within the power plant may contribute significant water savings and must be managed and executed diligently [14]. The author also found that by adhering to design specification and proper maintenance of the stations water network, 3% savings can be achieved [14]. The analysis conducted in this study was based on input water demands including prevailing leaks at the station and did not really resolve the water loses because of leakage. The importance of water quantification against expected values and identification of process deviations is the main driver of this research project.

Water accounting in a power plant that has variations in fuel source, cooling technologies, water sources, ash handling plants, climate conditions, and external service providers tends to become a challenging task. Hence, water management systems become extremely valuable when trying to assess the water performance at a power plant. The development of these tools, is therefore, usually based on the business requirements and system configuration.

The lack of these water management tools in Eskom affects how water targets are set for individual power plants. This also makes it extremely difficult for power plants to identify the plant areas contributing to high water consumption and improve performance. The lack of data also limits the attention to water efficiency in power plants [15].Thus, the development of a water balance model in real time can be of significant value to Eskom.

1.2 Purpose of study

This research is aimed at understanding water balance models for Eskom's coal-fired power plants, their defining characteristics, as well as to develop an integrated water balance model on an online software tool, EtaPRO. EtaPRO is a plant performance and monitoring tool which has the capability to receive real time data from the plant and use that to compare to design, target, and expected values.

The study will entail researching the behavior of various components within Eskom water systems and modelling these components using their fundamental equations. It will also entail identification of water flow paths, quantification of water consuming processes, and the development of a water flow network. A methodology for developing a water balance model in EtaPRO will be explored in the pursuit of creating standard calculation templates that can be used to set up water balance models for various power plant configurations. This will also create a foundation for future model developments in Eskom.

The primary objective is to provide Eskom with a method on how to develop a water balance model within EtaPRO.

1.3 Scope and limitations of research

The scope of this research is limited to wet-cooled coal-fired power plants and the use of the EtaPRO software.

The scope of the research is outlined below:

- Literature review on the architecture of water reticulation systems of wet-cooled power plants, including the water balance approaches for the respective power plant.
- Literature review of component characteristics and typical input assumptions made that fall within the water reticulation system.
- Assessment on the functionality of the EtaPRO monitoring tool.
- Develop a methodology for setting up a water balance flow diagram.
- Data collection for all sources and sinks identified in the literature review.
- Development of calculation templates for the various components within the water balance model.
- Development of a methodology for a water balance model on EtaPRO.
- Development of generic calculation templates describing the various process characteristics and flows within the water balance components identified.
- Documentation of the water balance model, component characteristics and flow balances.

The research will not address the following aspects:

- Fundamental physics models of the processes occurring at various locations, such as desalination, ion exchange and ash dam processes.
- Accumulation of water at various reservoirs.
- A comprehensive set of water balance models for all the various types of power plants in Eskom.
- Optimisation and water consumption reduction methods and/or technologies.

This research aims to provide a methodology of setting up a water balance in EtaPRO by using a standard framework. The calculation methods to obtain certain inputs can vary between power plants and therefore, this dissertation reviews the Eskom approach and provides recommendations of improvements where possible.

1.4 Outline of Dissertation

The fundamentals behind the water balance within a power plant will be discussed in Chapter 2 as a literature review. This will form the basis for the water balance model development, and will entail detailed descriptions of each system and the role played within the water balance model at a power plant. A review of water minimisation, the existing water balance tools used within Eskom, as well as the EtaPRO software functionality, will be discussed in Chapter 2.

Chapter 3 will outline the methodology followed in developing a water balance model that can be developed in EtaPRO using a combination of existing Eskom models and the literature captured in Chapter 2.

The results and observation of the implemented model will be discussed in Chapter 4.

Finally, Chapter 5 will capture the conclusion of the dissertation with some recommendations.

2. Literature Review

Water planning in countries can be viewed with the outlook in Figure 2, where water users in a basin are categorised into five main sectors [16]. Electric power can be seen as one of the five sectors due to its significant impact on withdrawal of water from various water catchments, as well as discharge to the environment [8].

Figure 2: The schematic representation of the five water use sectors [16]

Water availability and quality, as well as climate change, pose as risks to water dependent processes at power generating plants [16]. Power plants may also be facing more stringent thermal discharge limits that prove to be more difficult to meet when water consumption is high and dam levels are low [16]. Power generation utilities are increasing participation in water disclosure and foot printing activities such as research with the purpose of better understanding their current water use and providing reassurance to investors of the sustainability of their current and planned water use practices [16].

In order to establish a water balance tool, it is crucial to understand the technologies and processes that play a role in generating electricity at a coal-fired power plant in Eskom. The sections in this chapter will cover the following:

- Water balance tools.
- Water minimisation and optimisation review and application.
- The water balance theory and fundamentals.
- Process overview of a coal-fired power plant and its water and steam cycle integration
- Climate impact.
- The process of receiving, treating and utilising raw water within a typical power plant.

- The review of the current Eskom water balance tools.
- The review of the EtaPRO software.

The objective of this chapter is to cover the theory behind the water intensive processes at a coal-fired power plant and the tools available that will be used in the subsequent chapters.

2.1 Tools used for water balance models

According to an Electric Power Research Institute (EPRI) conference held to discuss various water balance models and tools, it was evident that this is not just a problem at Eskom but is seen as an area of improvement amongst most industries worldwide [17]. There is a definite need to improve water balance models and water accounting by developing models that are more robust. However, there is no consensus on which software platform can address these gaps. This is due to varying requirements on what the tools objective should be, thus making it difficult to choose one generic software to address all requirements. It should also be noted that most of these power plants are unique in some regard and similar in others making it challenging to develop generic water balance tools [17].

Microsoft Excel spreadsheets maybe used for simple flow balances but there is greater benefit in using models and simulation software [18]. Developing a dynamic (time-based) water balance model in Excel would imply the processing of large quantities of data. The more complex a water balance is; the more data is required to add more value. Hence, the integration of third party software is generally used for more dynamic water balances [18]. EPRI conducted an assessment on several generating plants in the United States to provide more information on various water balance modelling approaches, as well as their individual benefits. The study revealed that some power plants used Excel based tools, while others used third party or commercial software. The power plants using Excel based tools indicated that it lacked a user-friendly interface to display results and required both time and skill to develop. It also made comparing actual results to expected values tedious and was more suited to perform “what if” scenarios [19]. One benefit of the Excel models is that it provides a greater understanding of water recirculation systems and the various parameters that can be varied. Most power plants used Microsoft InfoPath and Excel tools for reporting [17]. The study showed the focus on water balances was more on withdrawals than on consumption, as was evident in the use of Excel tools. However, this is not an optimal solution for water balance development [17].

Water balances are complicated by the unavailability of data. Some power plants have shifted from Excel tools to web-based software using Python and Java script, or to using other tools to link to the plant data servers. This allows data to be collected via online systems. The EPRI study showed power plants used commercial software such as GoldSim, SOURCE, and DMS models [18].

GoldSim operates as a visual spread sheet where models are built in a hierarchical and modular manner by creating and linking subsystems together [20]. GoldSim has also been widely used in mining sites for the development of water balances [21]. Eskom has built water models on a similar software, STELLA, which is a systems thinking tool used to map out various scenarios [22]. STELLA has been used in several water production planning projects [23].

SOURCE uses ExtendSim as its software platform, which is used to develop models of dynamic processes [18]. SOURCE was originally developed to model and simulate clarification, filtration, and reverse osmosis processes. The Smart ChemWorks (SCW) software from EPRI has migrated away from Excel due to data security concerns [17]. The software is used mainly in the nuclear sector to perform real time data analysis, but can also be applied to fossil fuel plants [17]. However, further work is required to develop an entire water plant on SCW.

Most of the water balance models are based on the principle of module development of systems, and rely on the integration of other platforms for chemistry and plant data to work optimally. The assessment made by EPRI stated that instrumentation and data acquisition systems, which are often lacking, play a key role in accurately accounting for process water uses. The research also showed that there would likely not be one agreed upon software platform to meet all stakeholder requirements. However, any one of these software platforms can be used effectively for water management [19].

2.2 Water minimisation

The recent drive towards environmental sustainability and increasing costs of fresh water and effluent treatment have encouraged the process industry to find new ways to reduce fresh water consumption and wastewater generation [24]. This section will discuss briefly the principles and techniques for modelling water consumption and re-use. There has been extensive progress on the development of systematic techniques for water reduction, re-use and recycle within a process plant [24]. Process water management can be divided into two distinct activities: minimisation of freshwater requirement and optimal treatment of wastewater generated from the process [25]. Literature shows that by applying the concept of regeneration and recycling of wastewater, freshwater requirement can be reduced significantly while satisfying environmental regulations [25]. Reduced industrial water consumption is always accompanied by an approximate reduction in waste water disposal [26]. This simultaneous minimisation of fresh water intake and wastewater effluent can be collectively referred to as “water minimisation” [26].

Process integration is becoming an attractive solution to determine the most efficient re-use and recycle of resources within an operating system [27]. Principles of process integration, which were initially developed for the efficient use of energy, may be applied to address the issues related to water management in a process industry [25]. This can be achieved by proper modelling and exploiting the options for combining the water streams entering and leaving the various water using operations [26]. This section will discuss briefly the principles and techniques for modelling water consumption and re-use.

Three main design options can be considered when looking at process integration of water networks [28]:

- **Water re-use** – water can be re-used between operations.
- **Regeneration recycling** – water reclaimed from wastewater treatment can be recycled to the same operation either partially or fully.
- **Regeneration re-use** – water that is clean enough, can be re-used in other operations through wastewater treatment. The regenerated water is not supplied back to the same operation.

When analysing the water using operations for data extraction, the process must first be analysed to identify correctly the water use data. This includes data such as input and output streams, water flowrates and contaminant concentration. Next the purpose of the water use study should be defined as either minimising fresh water, wastewater discharge, or both [26]. The water minimisation options usually fall into two categories: re-use and recycling [29]. In both cases some water treatment can be applied, leading to two more options of regeneration-reuse and regeneration-recycling [29].

Water utilisation processes can be defined as mass transfer or non-mass transfer processes [30]. Mass transfer operations can be considered as quality controlled operations defined by the mass load of contaminants in a stream [26]. Non-mass transfer operations can be considered as quantity controlled operations. Non-mass transfer operations or water using operations are segregated into sink (fresh water intake) and source (waste water discharge) streams when analysed [31].

Two approaches exist to address the integrated process water management issues faced by industries: heuristic algorithmic procedures (insights based) which make use of graphical tools and procedures based on mathematical programming [28]. Application of these water minimisation techniques have had successes in industries such as refineries, petrochemicals, food pulp and paper and steel. Fresh water and waste water can be minimised by maximising the re-use of water within a process plant [26].

2.2.1 Insights based techniques

In 1989, El-Halwagi and Manousiouthiakis [32] proposed a methodology to target mass-exchange networks where contaminates from a set of rich streams are transferred to a set of poor streams [28]. A graphical method for targeting the freshwater requirement through water re-use and based on the more generalised mass-exchange network proposed by the previous authors, was proposed by Wang and Smith [29]. These methods are applicable for operating units which can be modelled as mass-transfer units [33]. This approach was based on the pinch analysis techniques for heat integration [29]. The introduction of water pinch analysis as a tool for the synthesis of water network has been one of the most significant advances in the area of water conservation [24]. The typical solution of a water pinch analysis is comprised of two steps. First is setting the minimum fresh water and wastewater flowrates, followed by network design to achieve the flowrate targets [24]. The water pinch analysis is a systematic technique for implementing strategies to maximise water re-use and recycling through integration of water using activities or processes [24].

Targeting procedures using the graphical approach

In water consuming operations, there is an increase of the mass load of contaminants in the water streams due to mass transfer from the process stream to the water stream [26]. This relationship can be represented graphically by a plot of mass load against contaminant concentration [34]. The maximum outlet and inlet concentrations of the water stream are required to identify any re-use possibilities. If the contaminant level of the exit water in an operation is lower than that required for the inlet water of another operation, water re-use is possible. The concept of the “limiting water profile” was introduced by Wang and Smith [29]. By specifying the maximum allowable inlet and outlet contaminant concentrations for each operation, a limiting profile can be constructed [34]. The mass load to be removed is obtained from the water flowrate multiplied by the concentration difference [26]. The allowable concentrations may be fixed by the following: mass transfer driving force, solubility, fouling and corrosion [29]. Once the limiting conditions are determined, no other operational conditions are required. This has significant benefit in allowing for an overall system evaluation in an integrated design framework.

The targeting procedure for the minimum water requirements is based on the graphical manipulation of limiting water profiles [29]. The first step is to create the “water composite curve” by combining the individual limiting water profiles [29]. Once the information on the limiting water profiles are known, the overall contribution from the limiting water profiles with the same concentration interval can be obtained. The composite curve will be the basis for the targeting and design of the water systems for water minimisation. This composite curve is a graphical representation of the total system cumulative mass exchanged within unit operations versus the cumulative composition changes within the system [29]. By assuming the freshwater is at a zero ppm concentration, a supply line is drawn from the y-intercept as illustrated in Figure 3 (b). The steeper line indicates reduced water requirements. The maximum slope for the water supply line can be found when the supply line touches the water composite curve creating a limitation. This point is known as the pinch point [29].

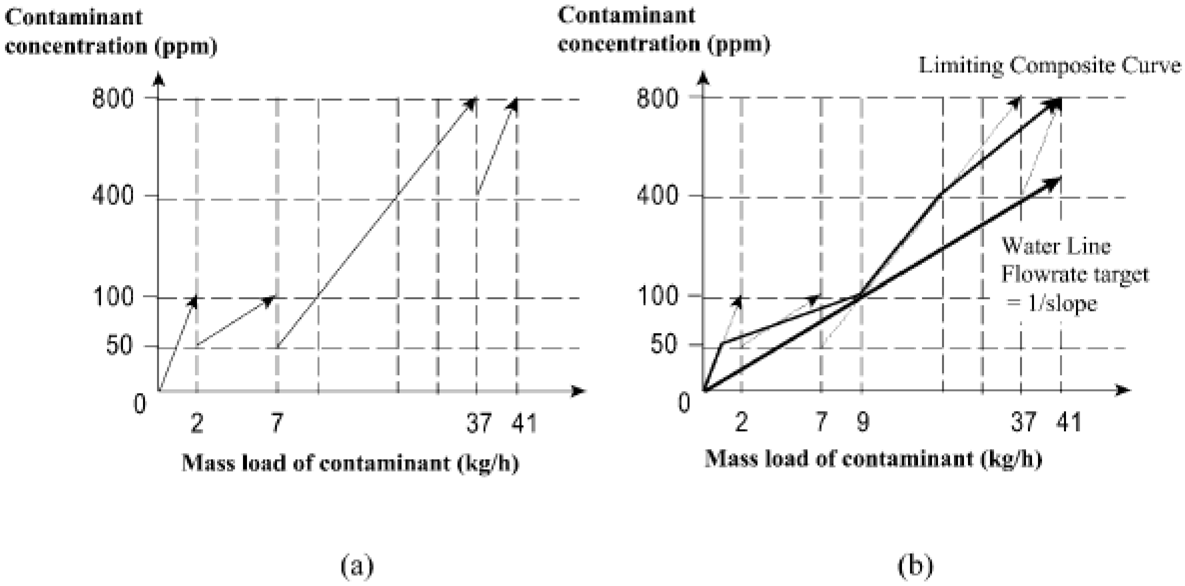


Figure 3: (a) Individual water using operations represented as contaminant mass transfer process. (b) Constructing of limiting composite curve and flowrate targeting [34].

Several key targets can be obtained from the graphical representation shown in Figure 3 [35]:

- The inverse slope of the supply line represents the minimum amount of freshwater required to satisfy all unit operation requirements.
- Subtraction of the inverse slope value from the total cumulative water required for all unit operations equals the amount of water that can be directly recycled or re-used within the process units.
- The pinch point represents the thermodynamic water quality bottleneck within the system of process units. This represents the point where fresh water will always be required. The composition target represents the point where it may be beneficial to add water purification technology.

The minimum flowrate obtained from the targeting procedure is used in the design stage, during which the network of water using operations is configured to meet the minimum water requirements for the whole system [26]. After the targeting step, rules are applied to derive a set of alternative network design structures. Each network obtained is evaluated for applicability and the most suitable one chosen [29].

Using the concepts of limiting composite curves and vertical transfer, minimum water consumption targets in systems with single and multiple contaminants can be calculated [29]. Research shows that regeneration of water streams was also considered [28]. Further research presented an extension of the methodology, considering stream flowrate constraints, water losses along the process, and multiple water sources and the introduction of local recycle and operation division concepts [28], [36].

This approach has been a major step in understanding water system design but comes with several limitations that resulted in further research projects [34]. Wang and Smith [29] developed an approach for the design of distributed effluent treatment systems. The method fails to predict the lowest possible target for the treatment flowrate in some cases and failed to address important features of the design for multiple treatment processes in both single and multiple contaminant cases [36].

Kuo and Smith [36] extended this procedure for multiple treatment processes and proposed an improved method for targeting treatment flowrate [36]. The research also addressed the distribution of load between multiple treatment processes [36]. The concept of wastewater degradation was introduced to account for treatment process sequence in multiple contaminant problems. The methods developed applied to the case of retrofit of which no systematic methods were available at the time of the research conducted [36].

The works of previous authors (Wang and Smith [29], Kuo and Smith [36]) handled the design task in two stages, i.e., the minimum process water consumption rate or wastewater treatment capacity was first determined according to a composite curve and the network structure was then obtained manually based on heuristic procedures. Shortcomings in this approach which require further attention are as follows [37]:

- With the water pinch analysis, it is difficult to identify the minimum freshwater rate or wastewater treatment capacity for multiple sources and sinks, and those containing both water using and water treatment operations that result in water losses.
- The manual construction of the composite curves and network structures makes it quite tedious.
- Inconsistencies may arise in the quality of the final design based on the user’s experience.
- The interactions between the water using, regeneration, and effluent treatment networks handled with an iterative procedure were still constructed individually. As a result,

opportunities of integrating different types of water consumption/treatment units within a unified framework may be overlooked.

This approach for designing a recycling network increases in complexity as the number of water sources and sinks increases [35]. Literature states that basing the methodology on a mass transfer model is a large drawback [34]. Furthermore, multiple inlet and outlet streams from an operation creates further difficulty in modelling [28].

Various targeting methods have been researched and proposed for water re-use and recycle. The first method for flowrate targeting for the fixed load problem was the source and sink composites [38], [34]. In this method each relevant operation is considered to have aqueous inlet and outlet streams, of which there can be several of these with varying flowrates and contaminates [34]. In this approach, all input streams are combined to form a demand composite, and all the sources are combined to form a source composite [33]. The overlap between the two composite curves show potential for water re-use. In order to achieve the targets, fresh water should not be used below the pinch point and sources above the pinch point should not be discharged. The difference in the construction of the plot is that the horizontal axis is the flowrate and the vertical axis is the composition [25]. However, targets given by this approach cannot be considered as true target as they depend on the mixing pattern, which is part of the network design [34]. Also to note is that the mixing of two streams can relax the pinch point decreasing the freshwater requirement [25].These composite curves are constructed after the network design and is developed using mathematical programming [34]. This approach is merely a graphical representation of a particular design. A true targeting approach would require the prediction of a minimum flowrate ahead of any design [34].

The water pinch approach does lack in obtaining high levels of accuracy due to its graphical nature. Graphical methods lack in analysing multiple contaminants simultaneously and is best addressed using mathematical programs. Water minimisation problems are not confined to concentration and flow rate constraints only. Other constraints such as economic, geographical and safety constraints also exist and these affect the optimal designs to be considered [26]. Additionally, cost constraints determine the economic feasibility of a design. It should also be noted that the water pinch technique is not a dynamic approach as is based on a fixed conditions for the selected period. Hence the solutions would be invalid with changes in process conditions and will have to be repeated.

2.2.2 Deterministic optimisation techniques

The insights based approach involves water pinch analysis techniques discussed earlier. These techniques provide key insights with low computational challenges and requiring significant problem simplification [41]. This section will touch on the mathematical optimisation techniques.

Optimisation allows rigorous treatment of large-scale complex systems by considering representative cost functions, multiple contaminants, and various topological involving high computational expense [41]. Various optimisation approaches have been developed to complement water pinch analysis in dealing with more complex problems [26].

Mathematical approach

Optimisation can be thought of as making the best choice among a set of available options. There exists some performance criterion, which is necessary to maximise or minimise, and is referred to as the objective function. Literature studies show that there is increased development of mathematical models of greater rigor and complexity driven by optimisation-based approaches, mainly mathematical programming [41]. Optimisation based techniques for re-use/recycle and regeneration networks also make use of property-integration framework [41].

Mathematical programming problems can be modelled by using either a fixed contaminant mass load framework or a fixed flow rate framework. Fixed mass load operations are quality controlled while fixed flow rate operations are quantity controlled [25]. Early approaches were mostly mass-load based while the later methods shifted towards a fixed flow rate framework [41]. The decision of which framework to adopt depends on the author's opinion and the availability of data [25].

The most common practice is the building of a superstructure involving all possible water re-use, recycle and regeneration options, followed by reducing the substructure employing optimisation techniques [41]. There are two major options for formulating the superstructure and subjecting it to reduction optimisation [26]:

- Explicit formulation of a superstructure translated into an integer programming model. Optimisation tasks involve the mixed integer non-linear programs (MINLP) but are frequently modelled using the linear models and give rise to mixed integer linear programs (MILP). The generated problem is solved using algorithms included in major commercial optimisation software packages such as GAMS.
- Automated generation of the maximal superstructure and the listing of all feasible water topologies using the P-graph framework. The water using operations can be described as the input to the automated procedure together with the compatible connections between them and the corresponding process and cost information. The procedures then apply algorithms.

Takama et al. [42] first proposed a non-linear programming formulation to solve the water allocation problem in a refinery[37]. The use of superstructures presented several numerical limitations, hence Takama et al [42] transformed the model into a sequence of unconstrained problems by using a penalty function and finally solving it using a Complex method. All superstructure models require large number of constraints to mathematically represent the component and overall mass balances

[43]. Infeasible solutions are often rendered when using straight non-linear programmes, therefore relaxation techniques need to be applied to solve the problem initially and retrieve feasible starting points [43]. However, there is still no guarantee over the optimality of the optimum [43].

After the pioneering work of Takama et al. [42] no journal publication addressed a mathematical programming formulation of the problem for several years [42]. However, there has since been a number of MINLP models developed by various authors [43]. Savelski and Bagajewicz [43] showed that the model for single component can be linearized [43]. They proposed an iterative method, which involved linear programming formulation for the optimal solution of the single contaminant problem and an MILP for the design of the different possible network alternatives [43].

After the pivotal paper by Takama et al. [42], water management in process plants has grown from a humble start in the early nineties to a mature field where complex situations are analysed and solved [43]. Throughout the years, the field has evolved from being dominated by the use of conceptual design procedures to the current almost exclusive use of mathematical programming [44]. However, practical numerical challenges are still apparent as well as some conceptual challenges. The findings through various research is that mathematical programming can produce globally optimal solutions and practically important sub-optimal solutions when conceptual insights are employed to build the models [43]. One of the shortfall of optimisation is that it does result in high computational expense to achieve optimality [41].

While all the above methods and the mathematical programming approaches have various degrees of success in solving the problem, data gathering and establishing proper constraints (maximum inlet and outlet concentrations) is a practical problem that has not yet been addressed fully [43].

Graphical and mathematical developments

Research conducted by authors Sorin and Bedard [39] led to the development of the Evolutionary Table approach [34]. This is a numerical method used to determine the fresh water and waste water targets without resorting to graphical solutions [39]. However, this approach fails where there is more than one global pinch point solution [33].

There has since been numerous developments to improve the efficiency of water systems and additional targeting approaches have been developed for water-based processes [30]. One such approach was the concept of the graphical water surplus diagram developed by Hallale [34]. This is particularly useful for industrial problems involving process units with different inlet and outlet water flowrates and compositions such as cooling towers, boilers and reactors [30]. The flowrate is the main concern in this type of operation and not the amount of contaminant picked up [30]. The water surplus diagram method was used for targeting the minimum freshwater requirement for fixed contaminant-load problems as well as fixed flow-rate problems [34]. This new targeting technique is purely graphical and therefore gives water targets a priori and not the design [34]. This is achieved by building in all mixing possibilities to determine the true pinch point and re-use targets. The water surplus diagram uses a similar representation to that proposed by Dhlole et al. [27]. In order to achieve the targets determined through this approach, a linear program problem is applied. The objective function is to minimise the total fresh water flowrate, subject to constraints such as flowrates and concentrations. The development of this methodology is quite tedious due to numerous calculations that are required, and there is a dependence of two graphs to satisfy flow rate and composition for the source-sink structure [33].

Also worth mentioning is work done by El-Halwagi et al. [33] on the material recovery pinch method. Manan et al. [30] developed the water cascade analysis method to ease the exercise of graphical iterations and was later improved upon by Foo et al [40]. Water targeting for batch processes was developed by Foo et al. [31].

Overall water management in a process industry is usually performed sequentially. The designs of water using processes are addressed first and subsequently, based on the designed water re-use network, the distributed effluent treatment system is designed [25]. This sequential procedure may lead to a sub-optimal solution for the distributed effluent treatment system. Takama et al. [42] solved the complete water management problem using nonlinear optimisation techniques [42]. Kuo and Smith [36] presented a methodology to discuss the interaction between operations that use water and effluent treatment systems [36]. Bandyopadhyay et al. [25] introduced a source composite curve-based approach for simultaneously targeting a distributed effluent treatment system and the minimum freshwater requirement [25]. A graphical representation and an analytical algorithm were proposed to address the integrated process water management issues that involve regeneration and recycle. All these methodologies have varying benefits and drawbacks. One of major issue raised is the need for “experts” and commercial software to apply the methodologies [35].

As with all process models, the water system model building starts with formulating the material balances. Material balances are written for the water flowrates and for the analysed contaminants alone. Due to complete analysis frequently not available, this should be accounted for during the model development. When complete results are available, then only can rigorous simulations of the optimised system be performed [26].

Very few companies have quantified water and energy use at unit process level [26]. Most industries know the approximate gross water usage but would not know categorically how the usage was apportioned between individual process lines or equipment. The lack of suitable quantitative data on water utilisation at production line level is a major driver for increased costs and non-compliance to legalization where effluent are generated [26]. The first principle for water management is to measure [19]. The rapid rates at which products and personnel often change affects water consumption. This can be attributed to inefficient accounting systems, and the split in responsibilities for individual aspects of water use [26]. Research has also shown that once of surveys can be quite inaccurate for current conditions [26].

A major feature of the water system design problem lies in the fact that the largest water users in a typical site are not mass transfer operations (e.g. cooling towers in power plants) [45]. Hence, it is important to establish the water balance for the process. Analyzing an existing process to complete the overall water flows is often a more difficult task due to the unavailability of detailed water flow records. It is recommended that at least 90% of the water in a process needs to be identified for a successful analysis [26]. This is to avoid missing significant water use or discharge flows. Next contamination data obtained should be analyzed to select as few as possible to represent the process in further analysis to reduce the complexity of the models. An increase in the number of contaminants selected increases the difficulty in visualizing the graphical target data. In addition, the number and nature of constraints to handle becomes difficult.

The identification of water using operations together with flowrate requirements and contaminate concentrations sets the scene for the model development. Larger concentrations at the inlet can enable more water outlets from other operations to be re-used. The actual water re-use will depend on the relative levels of concentration between the water sources and sinks. The use of fresh water and the discharge of waste water both have cost implications which can be expressed as functions of the corresponding flowrates. Thus, water flowrates must be obtained and made available for the water minimisation study.

Another factor to consider is the requirement of piping to new or existing systems which has additional cost implications. Water regeneration also has a certain cost associated to it and can be expressed in terms of the flowrate being treated.

Models often involve computational implementation with some mathematical descriptions. It is a much better practice to start with describing the concepts, formulating the mathematical relationships and finally implement the model computationally [35]. When dealing with water minimisation, applying insight knowledge specific to the process is important in improving the performance of systems [35].

A study was conducted on an Eskom power plant to research the possible reduction of raw water intake by applying process integration techniques to optimize the use of water available in the system [14]. The secondary objective was to reduce the wastewater produced within the process. The research showed that showed a significant amount of water ends up in station drains and the bulk of the water use is through the cooling towers. Hence, regardless if any other of the findings of the study was implemented, effective maintenance on cooling cycle equipment may reduce water consumption by as much as 5%. The findings in the report were based on input water demands including prevailing leaks at the station. The author also added the proactive identification and maintenance of any leaking equipment within the power plant could contribute to significant water savings and must be managed and executed diligently. The study found that by adhering to design specification and proper maintenance of the stations water network, 3% savings can be achieved without implementation of any of the other findings on water re-use.

The literature review on water minimisation has shown that it is necessary to first establish the water balance for the process prior any minimisation study. The water balance model is a crucial instrument to understand and manage water flows throughout the plant, to identify equipment with water saving opportunities, provide quantification and to detect leaks or misuse [46]. The inability to identify and quantify water is currently a major concern for Eskom. The availability of procedures and tools to quantify the water use within the process system and identify water losses is lacking in Eskom. The acquisition of water flow data is one of the great difficulties faced when constructing water balances in many industries [47]. It should also be noted that most streams in industry do not possess measurement devices and this inhibits the ability to construct a water balance [47].

The contribution of the this research is to provide a better understanding of the water consuming process, provide a methodology to develop a water balance model as well as set up such a model on an online monitoring tool. The setup of a water balance requires an initial survey of existing data, an assessment of major gaps in the available information and a decision on how detailed the water balance should be [46]. This can be used further as a basis for further research into optimisation and minimisation projects.

2.3 Water balance theory

When referring to the term "water balance", the immediate association is to the hydrological (natural) balance equation based on the principles of conservation of mass in a closed system [48]. This states that any change in the water content of a given volume during a specified period must equal the difference between the amount of water added to the volume and the amount of water withdrawn from it [48]. The hydrological balance of a catchment is described by Equation (1).

$$\dot{v}_{in} = \dot{v}_{out} \pm \Delta s \tag{1}$$

Where:

$\dot{v}_{in}$ = inflow of water to the hydrological unit (m^3/h)

$\dot{v}_{out}$ = outflow from the hydrological unit (m^3/h)

Δs = change in storage within the selected hydrological unit (e.g. catchment) (m^3/h)

The above equation is expressed in units of volume per unit time. When there are no other external flows to a catchment or water body, the general water balance equation can be depicted as shown in Equation (2).

$$\dot{v}_{rain} = \dot{v}_{runoff} + \dot{v}_{evap} \pm \Delta s \tag{2}$$

Where:

v_{rain} = precipitation (rainfall) (m^3/h)

v_{runoff} = run-off water (surface, subsurface or groundwater) (m^3/h)

v_{evap} = evaporation (m^3/h)

A water balance is a numerical account of how much water enters and leaves a plant, and where it is used within the plant [46]. The water balance is a useful tool for management and use of water in the production process [47]. Water balance models can be developed for various time scales (daily, monthly, or annually) making use of either average volume flowrates or total volumes over a specified period with various degrees of complexity [49]. However, the general approach taken entails defining a system boundary with process inputs and outputs to perform the mass balance of the system to ensure continuity over a selected period using time-weighted averages [19]. The methodology taken within the power generation sector will be described in more detail in Chapter 3 and will thus provide the foundation for the development of the water balance model.

Water balances in power plants are initially developed in the design phase of the power plant to correctly size equipment used to treat, produce, and convey water to the power plant [18]. The water balance model primarily consists of the process flows for all major streams on a plant schematic as indicated in Figure 1. Variations in the water balance exist due to load variations and climate conditions (summer, winter, and average conditions) that consist of wet and dry bulb temperatures, evaporation, and rainfall.

According to research done by EPRI, water balance models are developed either as a legal requirement for facilities to be Zero Liquid Discharge (ZLD) certified, or to manage either a surplus or deficit of water in the system [18]. Water balance developments were originally flow-based in order to satisfy the requirements of water conservation and the development of “what-if” scenarios [19]. Although water chemistry is an important aspect of the plant design, this was treated as a stand-alone aspect.

Water balance models can become quite complex requiring larger quantities of data input in order to achieve meaningful results. Hence, data requirements and flow measurements have a major influence in the development of water balance models[19]. Data inputs can be categorised into the following three sections [18]:

- Known data/calculations – power plant generating capacity, raw water source, chemistry limits.
- Design data – cooling tower evaporation rates, pump capacity, make-up requirements.
- Unknown – such as service/potable water used for housekeeping within the power plant.

There is a need for continuous improvement on water balance development. In the case where the water balance model forms part of a water management tool, the initial water balance development is considered the framework for an evolving model [18]. The complexity and accuracy of the model can be improved as more information is gathered.

The starting point of a water balance model is the development of the schematic, illustrating the water flows and interaction with process equipment. This requires the understanding of the processes within the system and its contribution to water consumption on the plant. The next section will provide further details on the coal-fired power plant processes required for the development of a water balance model.

2.4 Coal-fired power plant fundamentals

The representative power plant shown in Figure 4 below operates on what is known as the regenerative Rankine cycle.

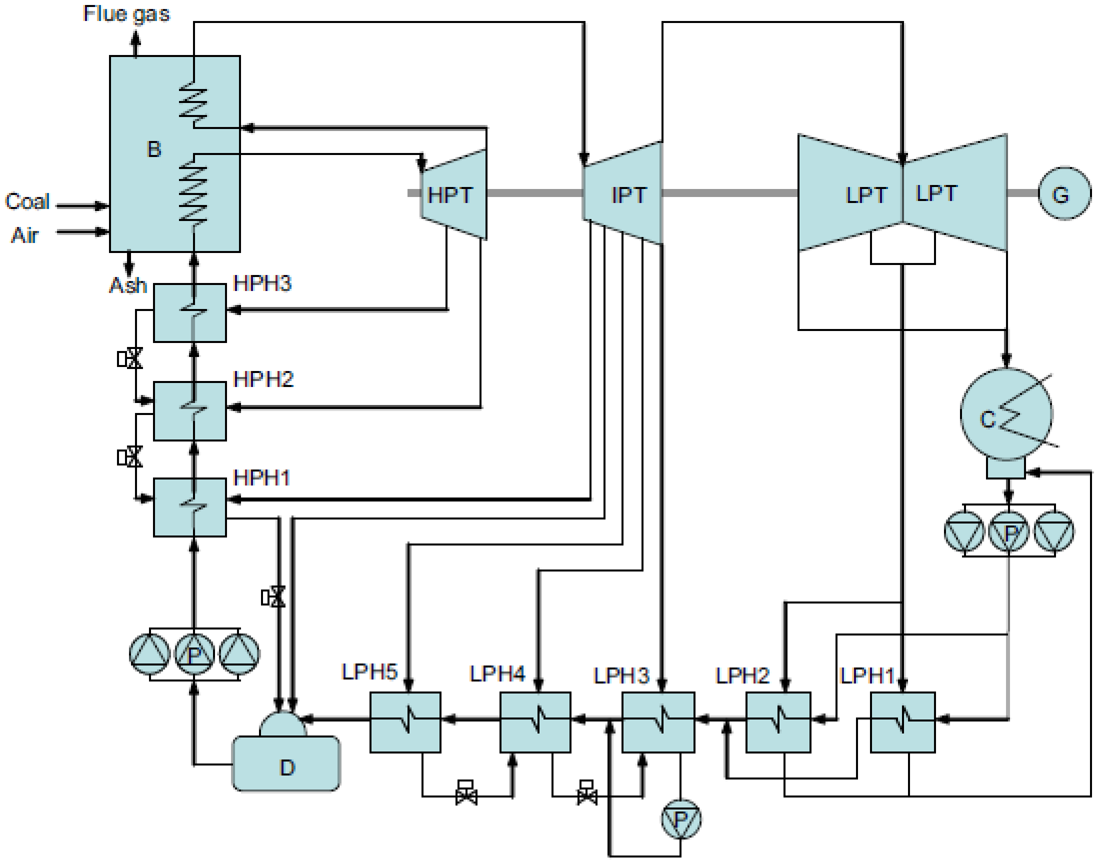


Figure 4: Schematic of a typical coal-fired power plant [50]

Coal, used as the primary fuel source, mixes with primary and secondary air streams resulting in combustion within the boiler. Chemical energy released from the combustion of coal is converted into thermal energy. The water circuit is a closed system with make-up water continuously flowing into the system as Demin water, which is introduced into the boiler via a Boiler Feed Pump (BFP). The Demin water, which flows within the boiler tubes, then absorbs the thermal energy from the hot gas stream passing over the boiler tubes. This results in an increase in fluid temperature until the Demin water is converted into superheated steam. This steam then expands through a series of steam turbines doing work, which converts the thermal energy into mechanical energy [13]. The mechanical energy is then converted into electrical energy within the generator, which feeds into the transformer. The steam exiting the turbine enters the condenser at a reduced temperature and pressure [51]. The condenser uses CW as the cooling medium to absorb what is considered as waste heat from the steam side and dissipates this heat through a cooling system. The resultant condensate from the condenser is then transported through Low Pressure (LP) heaters, a deaerator and back to the BFP. The BFP pumps the Demin water through a High Pressure (HP) heating system for pre-heating before entering the boiler once again.

The overall cycle energy efficiency of the regenerative Rankine cycle for a coal-fired power plant is very low, at approximately 35% [1]. This is due to approximately 55% of the chemical energy from the coal dissipated via the CW system. The remaining 10% of chemical energy is estimated to exit via the gas stacks [1].

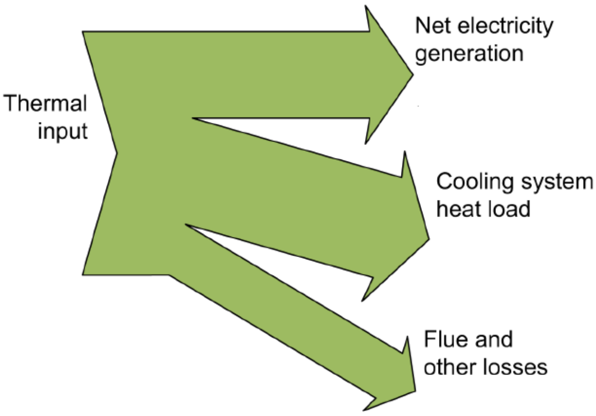


Figure 5: Simplified illustration of the energy conversion process of a coal-fired power plant [4]

In the Rankine cycle thermal power plant, a significant amount of make-up water is required due to boiler blowdowns, steam condensate losses, water evaporation loss in the cooling tower and blowdown discharge in the cooling tower [15]. This has led to an increase in attention from academia and engineering on the water issues at thermal power plants [15].

Water consumption depends largely on the load generated and the overall cycle efficiency of the power plant [13]. This is mainly because of evaporation from wet-cooling towers during the rejection of waste heat.

The net electricity output of a power plant can be obtained by applying equation (3).

$$\dot{W}_{net} = \left(\dot{W}_{gross} - \dot{W}_{aux}\right) \cdot L_f \tag{3}$$

Where:

$\dot{W}_{net}$ = nett electrical power output (kW)

$\dot{W}_{aux}$ = auxiliary electrical power output (kW)

L_f = load factor (dimensionless)

The Nett Heat Rate (NHR) of a coal-fired power plant is defined as the chemical energy required from the source fuel (coal) to deliver 1 kWh of electrical energy in kJ/kWh [52] and can be calculated using equation (4).

$$NHR = \frac{\dot{m}_{coal} \cdot CV_{coal}}{\dot{W}_{net}} \tag{4}$$

Where:

NHR = Nett Heat Rate (kJ/kWh)

CV_{coal} = Coal Calorific (CV) value, as received basis (kJ/kg)

$\dot{m}_{coal}$ = mass flowrate of coal (kg/s)

The thermal efficiency of a power plant in Eskom is defined as the quotient of the heat equivalent of 1kWh and the average NHR expressed in the same units. In Eskom, the term “overall thermal efficiency” implies the heat rate was calculated using the nett station production (KWh sent out) or Station Sent Out (SSO) [53]. Thus, the nett thermal efficiency, η_{th} ,is the heat content of electricity (3600kJ/kWh) divided by the NHR [54].

$$\eta_{th} = \frac{3600 kJ / kWh}{NHR} \tag{5}$$

Where:

NHR = Nett Heat Rate (kJ/kWh)

η_{th} = nett thermal efficiency (%)

Water loss in a power generation plant is lost via various streams. This is usually in the form of evaporation, absorption, or discharge (water lost through seepage from ash dams or released into the environment due to dam overflows).

The most significant losses are grouped as follows:

Evaporation

- Evaporation from the main and auxiliary CW systems.
- Evaporation from the ash dam/dumps and pools, ponds and reservoirs.
- Evaporation of Demin water from passing safety valves or steam/water leaks.
- Evaporation of Demin water during soot blowing and boiler blowdowns.

- Evaporation during the bottom ash quenching process.

Absorption

- Absorption as phreatic water by dried ash dams/dumps.
- Absorption on the Coal Stock Yard (CSY) after dust suppression.

Discharge

- Overflow of reservoirs or dams.
- Seepage into ground water.
- Accidental or deliberate discharge of polluted water to a public stream.
- Treated sewage, which is returned to a public stream.

Water sources at a power plant are usually grouped into the following sections below:

- Raw water supply from various catchment areas.
- Mine water sources due to contractual obligation, or a supplement to reduce raw water consumption.
- Rainfall.

In a power plant, the water reticulation system is segmented into definite plant areas for assessment of water flows. This allows for the establishment of boundary conditions for water balance calculations. These consist of the following plant areas:

- Raw water
- Cooling water
- Demin water
- Potable water
- Ash water
- Water treatment effluents
- Storm water
- Treated sewage water
- Mine water recovery
- Drainage system

2.5 Climatic impact

Each power plant is located in a specific quaternary catchment, rainfall zone, and evaporation zone as categorised by National Governing Bodies [1]. The nearest weather stations are used when performing water performance calculations. Information from these weather stations are used in quantifying the impact of the local climate conditions on the power plant water balance. The parameters monitored and trended over time are rainfall, evaporation rates, and ambient temperatures.

Climatic conditions play a crucial role in the water balance development as it influences pond evaporation and rainfall collection [55]. It is necessary to understand these trends, as weather is a seasonal function that impacts the outputs of the water balance depending on whether the water balance is developed for a day, month, or per annum. Therefore, trends developed from reliable weather sources over the years can be used as an input to an annual water model. However, for daily water balances, real time data will be required for accurate modelling and comparison studies.

Figure 6 shows a trend illustrating the changes in climatic conditions for the period of 2017 on an average monthly basis. The variation in the precipitation between the driest and wettest months is 164 mm and the dry bulb temperature varies by 7.4 °C for the year of 2017 [56]. Temperature tends to follow a cyclic pattern as it is seasonal, and this repeats itself based on historic return periods. Trigonometric functions are commonly used to predict and model cyclic behaviour, therefore average annual high temperature can be mathematically modelled with sine and cosine functions. This cyclic behaviour is also evident when looking at daily data, allowing the development of daily functions. Figure 6 also indicates that evaporation rates and rainfall patterns follow the temperature profile as well.

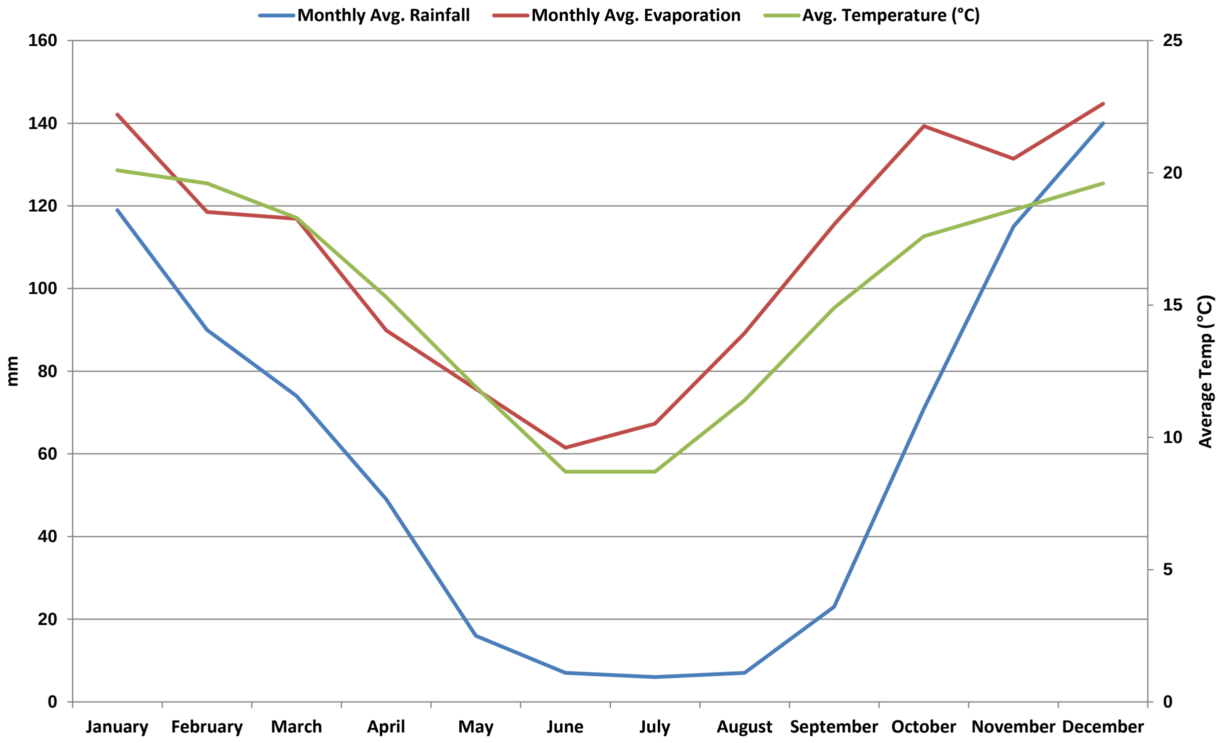


Figure 6: Climatic changes over the year 2017 using monthly averages [56]

The approach generally taken when setting up a water balance at a power plant is to use historic trends to predict average annual values for temperature, rainfall, and evaporation rates [19]. The climate profiles should be factored according to the period (daily, monthly, or annually) of the model to increase accuracy [55]. Weather station data available at the power plant or from nearby power plants will provide the most accurate source of information.

When calculating evaporation rates, pan factors are applied as a correction factor for evaporation rate calculations [57]. Pan factors convert evaporation rates from microclimate to macroclimate conditions [55]. Rainfall calculations are explained in Section 2.9.

2.6 Raw water system

Raw water is supplied from specific raw water dams (catchments) for each power plant and the water qualities may thus vary from site to site depending on the raw water source. Eskom power plants receive raw water from different water catchments based on their geographical locations. The map in Figure 7 illustrates the location of Eskom's power plants relative to the raw water dams within the various catchments.

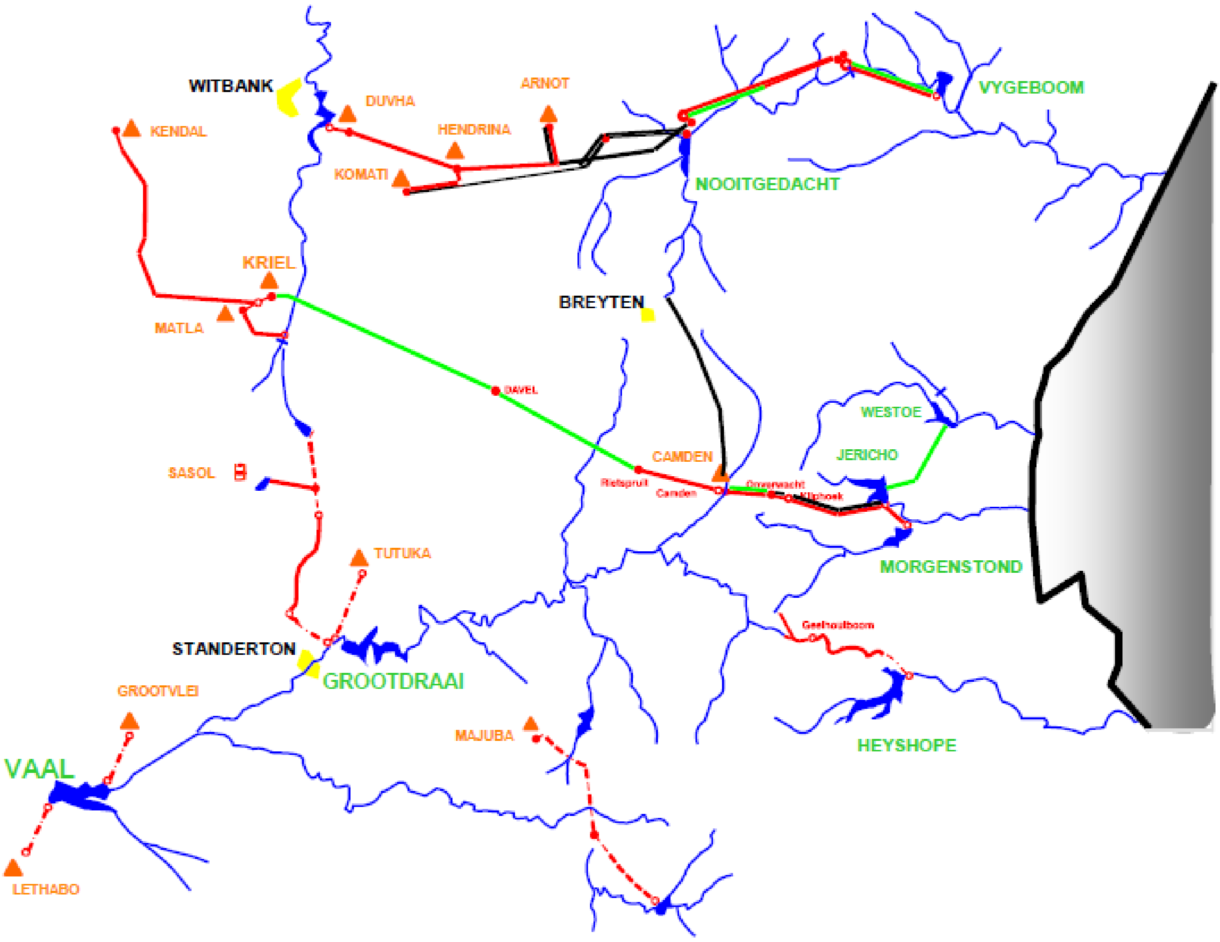


Figure 7: Eskom's raw water supply network [1]

Each raw water catchment has a specific water quality associated with it. The term "water quality" refers to the physical, chemical, and microbiological characteristics of water [58]. This quality also has a varying range based on seasonal changes. Consistent analysis of raw water supply quality that enters the power plants raw water reservoir is therefore a critical requirement.

When designing the Water Treatment Plant (WTP), the raw water quality forms the basis of the design for the plant equipment and processes, and most often becomes the limiting factor. Hence, the importance of accurate and frequent raw water analysis for process calculations, such as make-up requirements and WTP performance calculations is dire.

Raw water is pumped via centrally managed pumping stations to the raw water reservoirs. Figure 8 depicts the input and outputs of the raw water reservoir. Raw water reservoirs are usually open storage dams, and therefore experiences gains and losses due to rainfall, and evaporation. The outlet flow of the reservoir typically splits into streams for CW make-up use and/or pre-treatment via clarification.

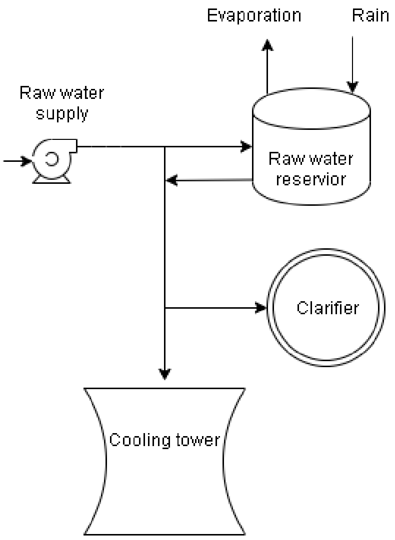


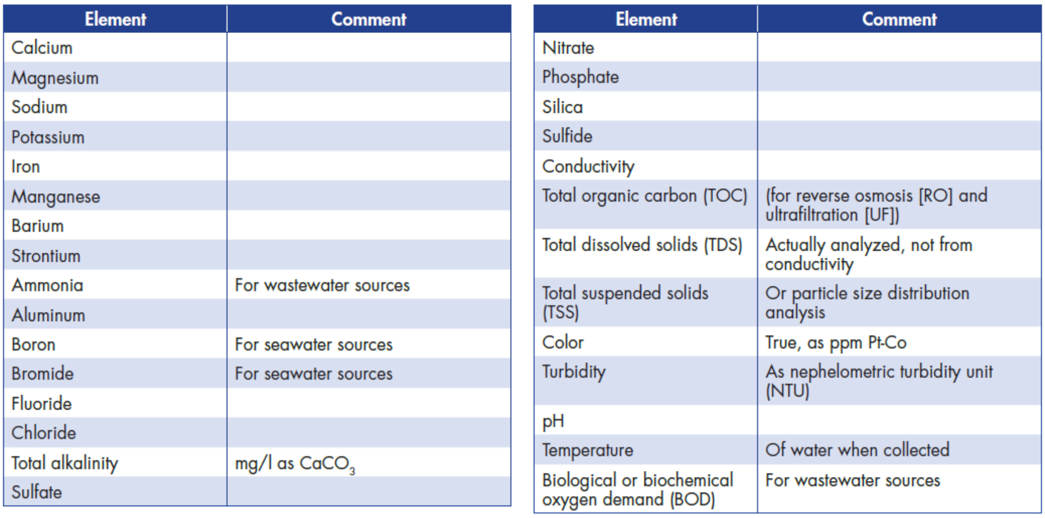
Figure 8: Schematic representation of a typical raw water schematic

The demand for potable, Demin, and CW make-up water by the power plant dictates the raw water consumption. Eskom power plants are generally designed with a split of approximately 90% of raw water as CW make-up water, and 10% of raw water for potable and Demin production.

2.6.1 Raw water analysis

All water sources (well, surface, wastewater, and seawater) contain dissolved minerals. The only exception is Demin water [59]. Table 2 provides the common soluble species in fresh water sources and their chemical symbols with the most common valance state (charge). Raw water analysis determines which elements are in a water source, their concentrations, and properties of the water (such as conductivity and pH). This is used for the control of downstream water treatment processes in order to achieve the chemistry standard limits specified for the power plant [60].

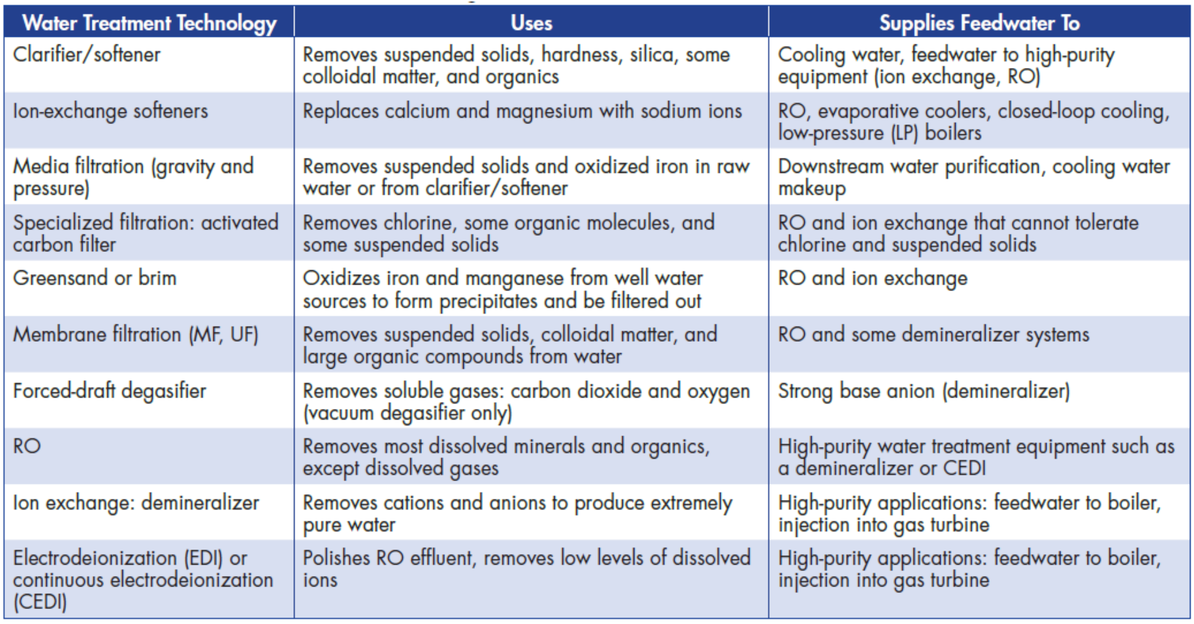
Table 2: Typical chemical parameters analysed in raw water [59]



Element	Comment
Calcium	
Magnesium	
Sodium	
Potassium	
Iron	
Manganese	
Barium	
Strontium	
Ammonia	For wastewater sources
Aluminum	
Boron	For seawater sources
Bromide	For seawater sources
Fluoride	
Chloride	
Total alkalinity	mg/l as $CaCO_3$
Sulfate	
Nitrate	
Phosphate	
Silica	
Sulfide	
Conductivity	
Total organic carbon (TOC)	(for reverse osmosis [RO] and ultrafiltration [UF])
Total dissolved solids (TDS)	Actually analyzed, not from conductivity
Total suspended solids (TSS)	Or particle size distribution analysis
Color	True, as ppm Pt-Co
Turbidity	As nephelometric turbidity unit (NTU)
pH	
Temperature	Of water when collected
Biological or biochemical oxygen demand (BOD)	For wastewater sources

Power generation plants are generally designed to receive specific raw water qualities for which water treatment plants are designed. This is to ensure Demin, potable, and cooling water are produced to meet internal chemistry standards, as well as plant design conditions [60]. Hence, the water treatment technology employed at each power plant varies depending on the raw water source and treatment requirements [58]. The various water treatment technologies are defined in Table 3 with its associated applications.

Table 3: Overview of various raw water treatment technologies [59]



Water Treatment Technology	Uses	Supplies Feedwater To
Clarifier/softener	Removes suspended solids, hardness, silica, some colloidal matter, and organics	Cooling water, feedwater to high-purity equipment (ion exchange, RO)
Ion-exchange softeners	Replaces calcium and magnesium with sodium ions	RO, evaporative coolers, closed-loop cooling, low-pressure (LP) boilers
Media filtration (gravity and pressure)	Removes suspended solids and oxidized iron in raw water or from clarifier/softener	Downstream water purification, cooling water makeup
Specialized filtration: activated carbon filter	Removes chlorine, some organic molecules, and some suspended solids	RO and ion exchange that cannot tolerate chlorine and suspended solids
Greensand or brim	Oxidizes iron and manganese from well water sources to form precipitates and be filtered out	RO and ion exchange
Membrane filtration (MF, UF)	Removes suspended solids, colloidal matter, and large organic compounds from water	RO and some demineralizer systems
Forced-draft degasifier	Removes soluble gases: carbon dioxide and oxygen (vacuum degasifier only)	Strong base anion (demineralizer)
RO	Removes most dissolved minerals and organics, except dissolved gases	High-purity water treatment equipment such as a demineralizer or CEDI
Ion exchange: demineralizer	Removes cations and anions to produce extremely pure water	High-purity applications: feedwater to boiler, injection into gas turbine
Electrodeionization (EDI) or continuous electrodeionization (CEDI)	Polishes RO effluent, removes low levels of dissolved ions	High-purity applications: feedwater to boiler, injection into gas turbine

The raw water analysis for a selected power plant receiving water from the Komati system, is illustrated in Table 4 with the subsequent sub-system analyses for potable, Demin, and cooling water streams. The data obtained from the raw water analysis can be used for Cycles of Concentration (COC) calculations or pre-treatment optimisation. The COC calculation and explanation will be discussed in detail in Section 2.8.3.

Table 4: Typical water analysis for streams within a power plant [57]

Parameter	Units	Raw water	Potable water	Demin water	Cooling water
PH	NA	7.8	8.96	7.0	8.1- 8.5
Electrical conductivity	μScm^{-1}	134	148.8	0.06	< 2500
Calcium as $CaCO_3$	$mgkg^{-1}$	27	25.4	Nil	100 - 300
Magnesium as $CaCO_3$	$mgkg^{-1}$	29.5	30	Nil	80 – 220
P Alkalinity as $CaCO_3$	$mgkg^{-1}$	Nil	5.4	Nil	0 - 7
M Alkalinity as $CaCO_3$	$mgkg^{-1}$	50.6	57	Nil	80 - 120
Sodium	$mgkg^{-1}$	5.6	7.96	< 0.002	30 – 80
Potassium	$mgkg^{-1}$	1.04	1.12	< 0.001	40 - 80
Chloride	$mgkg^{-1}$	3.5	5.5	< 0.001	20 - 50
Sulphate	$mgkg^{-1}$	8.21	7.45	< 0.001	< 750
Silica as SiO_2	$mgkg^{-1}$	7.3	0.33	<0.003	< 150

2.7 Water treatment at Eskom coal-fired power plants

Raw water is usually stored in raw water reservoirs to ensure constant supply via large pipelines to the water treatment plants [58]. Raw water can be split into various streams depending on the plant configuration. Of the 10% of raw water to the treatment plant for Demin and potable water production, a larger portion is utilised for potable water production, usually estimated as two thirds of the 10% of raw water supplied [61]. However, this can vary based on the requirements of the power plant. A typical distribution of raw water for a wet-cooled coal-fired power plant is illustrated in Figure 9.

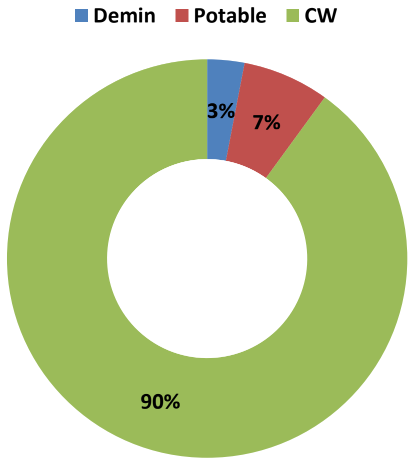


Figure 9: Raw water distribution for a typical wet-cooled power plant [57]

2.7.1 Raw water clarification

According to Table 3, there are various raw water pre-treatment options depending on the raw water source and the treated raw water quality required by the power plant. A common and economically viable technology on most power plants is the use of clarifiers for pre-treatment purposes. Eskom water treatment plants make use of this type of technology for pre-treatment of raw water.

A clarifier is a process component that is designed to reduce the Total Suspended Solids (TSS) from the raw water supply [62]. Clarifiers typically operate at a slow rate (high residence time), and provide a large surface area for suspended solids to settle and be removed in the form of sludge (solids and water) [59]. Clarifiers make use of coagulants and flocculants for chemical treatments, with the dosing usually occurring prior to the clarifier in the raw water supply line.

Coagulation occurs when a coagulant is added to water to “destabilise” colloidal suspensions in order to clarify the raw water [58]. The coagulant chemical collects suspended solids in the raw water by attracting them to the coagulant, which is positively charged, due to opposite static charges between the particles and the coagulant. Common coagulants are ferric chloride, ferric sulphate, and liquid alum. Coagulants can also be specially formulated long-chain polymers. The optimum dosage of coagulant is determined by performing jar tests on the raw water supply [59].

Flocculation causes aggregation of small destabilised particles, as a result of coagulation, to form larger aggregates so that they can be easily separated from the water phase [58]. The differentiation between coagulation and flocculation is that coagulation is a chemical process involving neutralisation of charge, whereas flocculation is a physical process that does not involve neutralisation of charge [59].

Apart from clarification, softeners may be required due to the raw water specific hardness in the form of calcium, magnesium, and soluble silica [58]. Softeners are used to reduce the natural hardness of the water by means of precipitation, using either lime , soda ash, or both. Softeners also play a role in the removal of suspended solids from raw water within clarifiers.

There are various types of clarifier technologies, which include solids contact clarifiers, inclined plate clarifiers, inclined plate separators, inclined plate settlers, or recirculating solids clarifier. The solids-contact clarifier mixes solids from the clarifier with the incoming water and chemicals to improve the efficiency of the clarification or softening process. This is the most common type of clarifier.

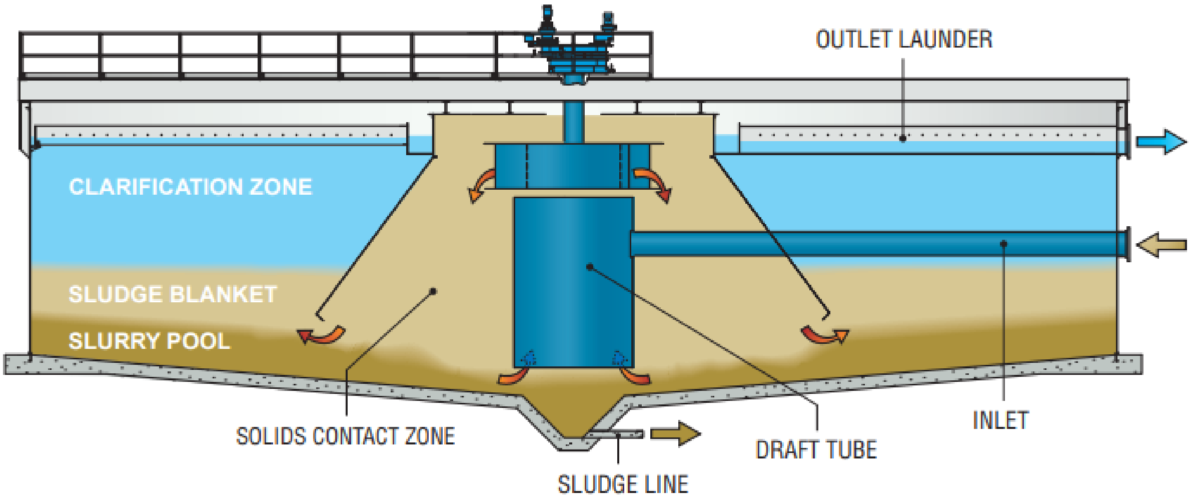


Figure 10: Schematic of a solids contact clarifier [63]

Recirculating Solids Clarifier

The operation of the recirculating solids clarifier entails the entry of water from the side or from the bottom of the clarifier, which is directed to the centre of the clarifier. The addition of chemicals can occur in either the raw water line or mixing zone. The mixing zone, which consists of fine slurry and chemicals, overflows into the larger reaction zone. The reaction zone is where solids pulled up from the bottom of the clarifier, mixes with the raw water and the added chemicals. The reaction zone can be characterised as a tapered cone resulting in a reduction in water velocity. The reduced velocity allows for completion of chemical reactions and commencement of the settling process [59]. The water exits the clarifier through a collection of laterals at the top of the clarifier after moving up through the reaction zone and sludge blanket [58]. A motorised system, such as a rake or bridge and stirrer, move the settled solids towards the centre of the clarifier where it is either pulled up into the mixing zone or discharged via blowdowns.

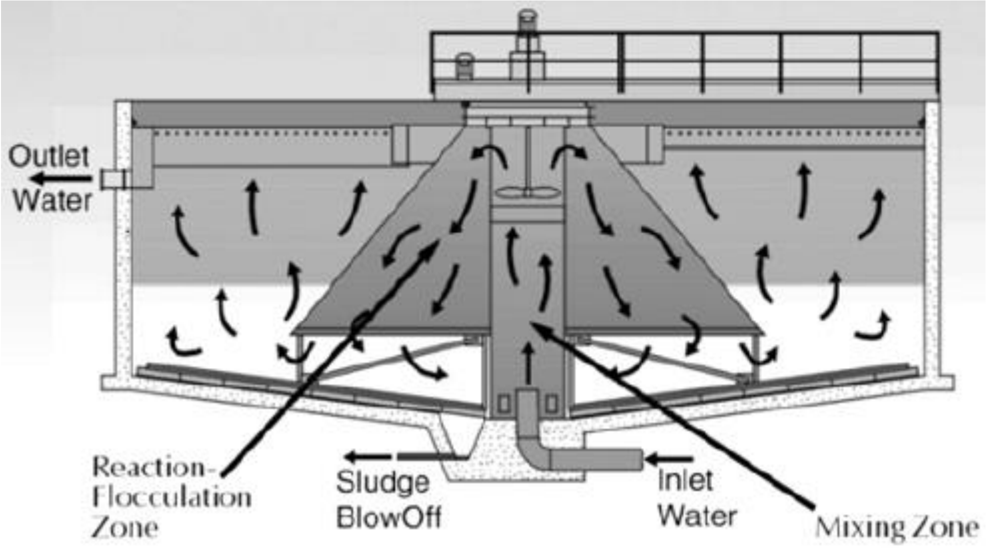


Figure 11: Upward flow sludge blanket [10]

The sludge production from the settling process can be expressed by equation(6) [62].

$$m_s = \dot{v}_w \cdot C_{ss} \cdot f_{ss} \tag{6}$$

Where:

m_s = average daily sludge production (kg SS/day)

$\dot{v}_w$ = average flow rate of feed water (m^3/d)

C_{ss} = suspended solids (SS) average concentration in the effluent wastewater (mg/L)

f_{ss} = fraction of SS removal in the primary clarification

In order to simplify the calculation, the sludge density can be approximated to that of water. This is a fair assumption to make as the percentage of dry solid sludge is relatively small (2% to 6% in primary clarifiers) to the total volume of sludge [64]. For a sludge volume of 1000L, this can be approximated to an error of less than 1% if the sludge concentration is below 3% [64]. Literature shows that the density of sludge is 1003kg/m^3 – 1010kg/m^3 for the 2% to 6% range of dry solids [64]. The actual sludge density can be replaced with measured values where these measurements exist, but this occurrence is quite rare at power plants. The historic percentage solids found in Eskom power plants is less than 5% [65] which is in line with typical values found in literature [58].

Hence, assuming that the sludge density is the same as that for water, the sludge volume flow rate can be calculated using equation (7).

$$\dot{v}_s = \frac{m_s}{\rho_W \cdot C_s} \tag{7}$$

Where:

$\dot{v}_S$ = average primary sludge flow rate (m^3/day)

C_S = primary sludge concentration (%)

ρ_W = density of water (kg/m^3)

2.7.2 Potable water production

Potable water forms a much smaller percentage of the total water usage and is usually in the region of 6% to 8% of the total raw water consumed [10]. Potable water is produced via a clarification process as discussed in Section 2.7.1. This process consists of raw water entering a potable water clarifier, sand filter, and then treated via chlorination and stabilisation [58].

After the process of clarification, the clarified water still contains solids, which are not suitable to produce potable and Demin water downstream [58]. There exists a process of filtration to ensure the turbidity of the water meets the required chemistry standard specified by the power plant. Turbidity provides an indirect indication of suspended and colloidal matter in the water and is expressed in either Nephelometric Turbidity Unit (NTU) or Jackson Turbidity Unit (JTU) [10]. Various filtration methods are available to remove particulate and/or other species from the raw water. Granular filter media for suspended solids removal generally contains one or more of the following media [59]:

- Anthracite
- Sand
- Garnet

Eskom has adopted sand filters as the form of filtration technology. The filter media within the sand filter may also be selected based on the treatment of specific impurities. The various types of filter media and its uses are [59]:

- Manganese green sand – removal of iron and manganese in well water.
- Activated carbon - removes excess chlorine or some naturally occurring organic matter.
- Granular (Gravity type and Pressure type) – operation is based on pressure drop across the filter which should be maintained within predefined limits. Upon exhaustion, the filter is

cleaned using either air scouring or a subsurface wash step with water to remove suspended solids. The final cleaning process includes back washing and forward rinsing steps.

Pressure filter media operation

Figure 12 illustrates a typical pressure filter with backwash. The pressure filter media is controlled either by monitoring the pressure drop across the filter or the outlet water quality. It makes use of backwash or rinse cycles for cleaning as and when required. The backwash flow is counter current to the filtration flow in order to attain a minimum of 30% bed expansion [59]. The backwash water is usually recovered back into the CW system for Eskom power plants. The rinse step allows for the removal of residual suspended solids following back washing and operates co-current to the filtration flow.

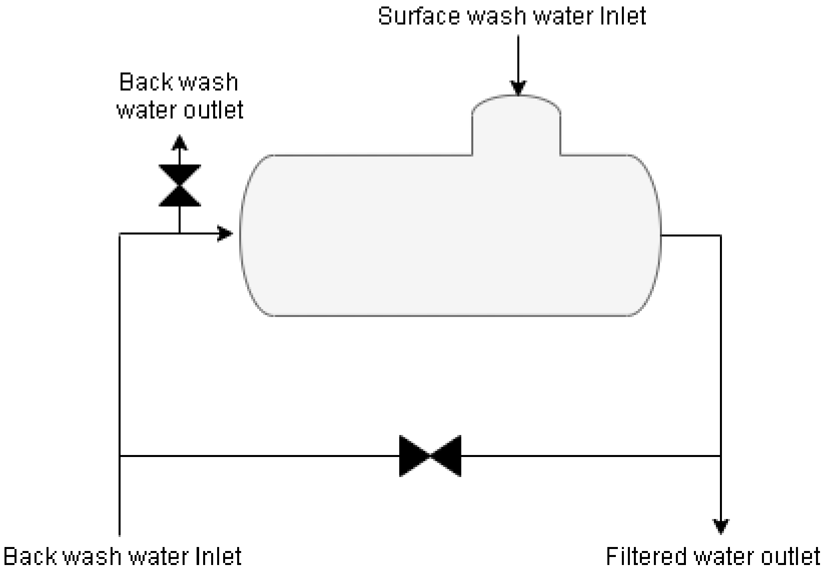


Figure 12: Typical pressure filter with backwash

The potable water produced is used for both internal and external (third party) use. Third party use of potable water consists mainly of the power plant mine and/or hostels. The power plant uses potable water internally for various reasons which may include fire water, sealing water on the turbine and boiler plant auxiliaries, ablution facility, small cooling systems, irrigation, floor washing, and general consumption [10]. Consumers of potable water define the potable water demand in a power plant. One approach to calculating the design demand on potable water supply is to assume consumption per capita and the average number of employees on site.

The calculation is given by equation (8).

$$\dot{v}_p = n_{emp} \cdot U \tag{8}$$

Where:

$\dot{v}_p$ = volume flowrate of potable water used for domestic activities (m^3/day)

n_{emp} = number of employees

U = usage of potable water per capita (m^3/capita per day)

As an example, an average usage of 200 L/capita for 1000 people will result in a 73 Ml/annum usage. Usage of potable water for floor washing, equipment cooling, and other activities on site, is not usually measured and is assumed from historical data. The potable water system can be a huge water saving area by applying techniques to quantify and identify the use and misuse of potable water. Potable water is often supplied by the fire water pumps at power plants. Figure 13 shows a typical pre-treatment water distribution between the potable and Demin plant.

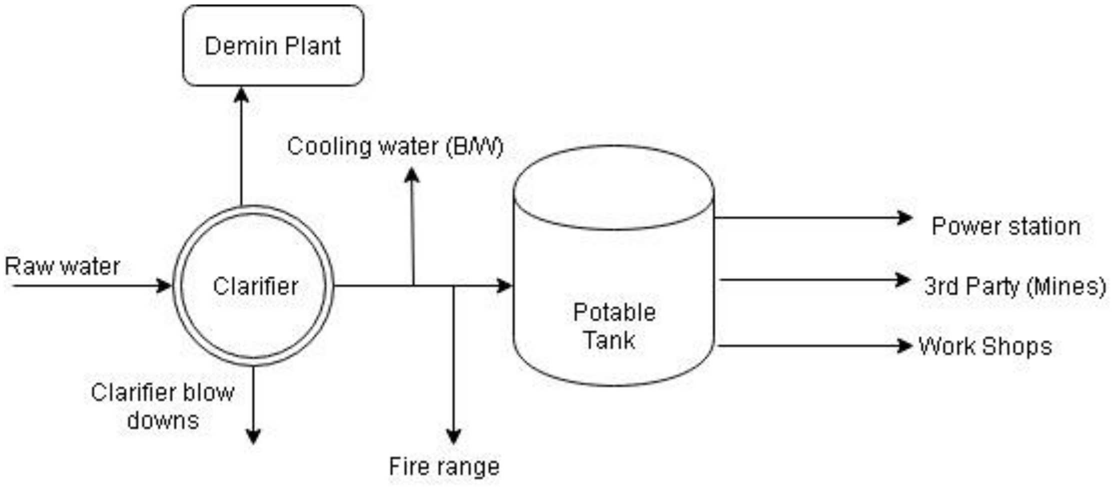


Figure 13: Typical pre-treatment process schematic

2.7.3 Demin water production

Demin water forms the smallest portion of the total raw water required, and is usually around 3% to 4% of the total raw water consumed [10]. Demin water is primarily used in the boiler for steam generation, and condenser as Demin water make-up [66]. This is due to Demin water lost via processes that entail Demin evaporation and blowdowns [15]. Demin losses mainly occur via boiler blowdowns (boiler drains) and turbine drains during start up and shutdown activities. Demin evaporation losses usually occur during normal operation via boiler and air heater soot blowing, spray water activities, steam leaks, or vents. Station Thermal Efficiency Performance (STEP), which is an Eskom tool, exists on the EtaPRO software to account for efficiency losses and gains [67]. One of the losses calculated in the STEP tool is Demin make-up loss. Eskom assumes that approximately 50% of the Demin water sent to the plant evaporates at steam conditions while the balance ends up in the station drains at feed water conditions [53].

The production of Demin water consists of clarification, filtration, and ion exchange (IX) processes or reverse osmosis and membrane technologies. Wastewater, such as backwash, is usually recovered back into the process via the CW system. Water treatment effluent is produced as a final waste stream, which is discharged to the ash water dams. The water treatment process consumes significant amounts of power, heat, and/or chemicals [15]. Hence, the process of Demin water production is a significant consumer of Demin water in itself, as it uses Demin water for resin regeneration processes.

2.7.3.1 Demin production through Ion Exchange (IX)

The process of demineralisation involves the removal of salts and minerals contained in the water [68]. The most common technology for Demin water production is via ion exchange [66] The process of ion exchange is a reversible interaction of ions between a solid and solution phase [69]. This process entails the replacement of ionic impurities in solution with hydrogen and hydroxide ion to make it suitable for steam generation within the boiler [66].

There are two basic types of ion exchangers [68]:

- Cation resin exchanger - uses resin to remove positively charged ionic impurities and replace them with hydrogen ion (H+).
- Anion resin exchanger - uses resin to remove negatively charged ionic impurities and replace them with hydroxide ions (OH^-).

The Demin plant design, configuration, and operational use of IX resins within power plants vary depending on the raw water that is to be treated, as well as the quality and quantity of the Demin water to be produced [59]. Mixed bed IX is responsible for achieving the strict Demin water limits set by the power plant and is generally the last system in the water treatment process as it is susceptible to resin fouling [66].

The general layout of a Demin production plant consists of a train or multiple trains of separate vessels of H+ cation resin, degasser, OH^- anion resin and a mixed bed vessel containing a mixture of H+ cation resin and OH^- anion resin [59]. Figure 14 illustrates the layout of a typical IX resin vessel used in Demin water production.

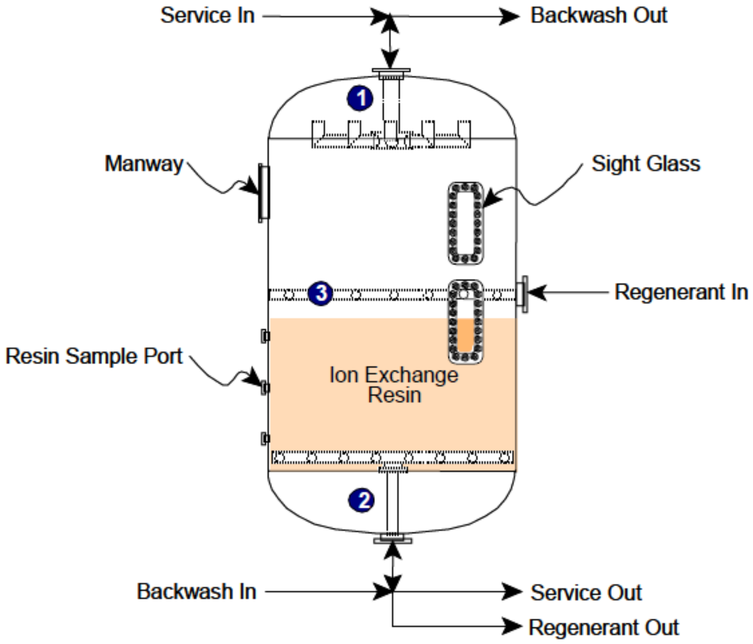
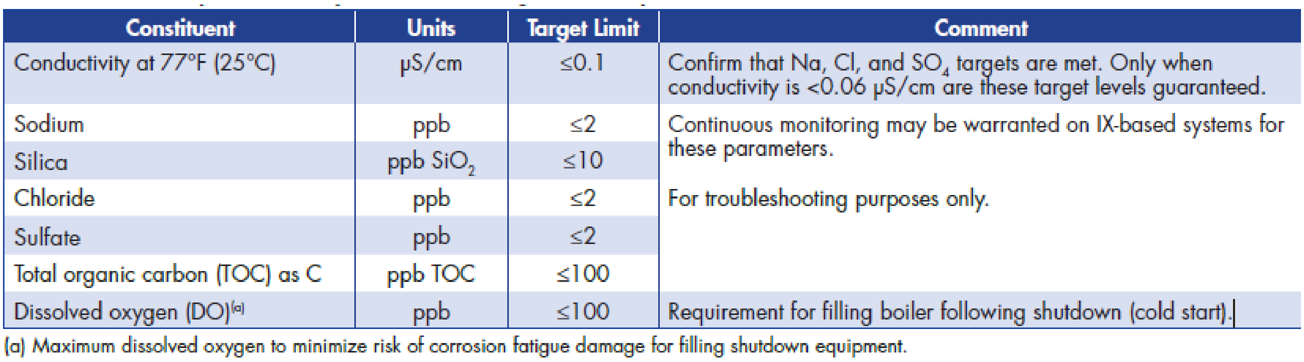


Figure 14: Typical ion exchanger vessel [23]

In order to achieve effective resin performance, the quality of pre-treatment water is required to be within specific limits. Table 5 shows a typical breakdown of the Demin chemistry limits.

Table 5: Typical Demin production chemistry limitation according to EPRI research [59]



Constituent	Units	Target Limit	Comment
Conductivity at 77°F (25°C)	µS/cm	$\leq$0.1	Confirm that Na, Cl, and SO_4 targets are met. Only when conductivity is <0.06 µS/cm are these target levels guaranteed.
Sodium	ppb	$\leq$2	Continuous monitoring may be warranted on IX-based systems for these parameters.
Silica	ppb SiO_2	$\leq$10	
Chloride	ppb	$\leq$2	For troubleshooting purposes only.
Sulfate	ppb	$\leq$2	
Total organic carbon (TOC) as C	ppb TOC	$\leq$100	
Dissolved oxygen (DO)[a]	ppb	$\leq$100	Requirement for filling boiler following shutdown (cold start).

(a) Maximum dissolved oxygen to minimize risk of corrosion fatigue damage for filling shutdown equipment.

Changes in raw water quality and operation of vessels can impact the rate of exhaustion of the resin, and hence also its lifespan [66]. Exhausted resin beds undergo a process of regeneration to restore the capacity and performance of the resin. The regeneration process entails several process steps, which consist of back washing the resin, then addition of chemicals, and the rinsing of the resin itself. These processes can vary depending on the type of resin, configuration of plant, and operating temperatures. The regeneration process can consume a significant quantity of Demin water with backwashes ranging between 6m^3/hr to 60m^3/hr per backwash on a single vessel [59]. The regeneration process is a major contributor to effluent production in the Demin production process, as this water cannot be recovered back into the system without further treatment due to its poor water quality. Hence, correct operation and optimisation of the Demin plant is crucial in trying to reduce the effluent produced within the WTP.

2.7.3.2 Condensate Polishing Plant (CPP)

Condensate polishing systems remove suspended and dissolved contaminants from steam condensate exiting the condenser in a power generating plant. These systems are designed to produce condensate that is within acceptable chemistry limits for boiler operation. Treatment is required for make-up water because boiler feed water has a strict requirement for protecting boiler tube and turbine blades [15]. Figure 15 illustrates the location of the Condensate Polishing Plant (CPP) in a power plant cycle.

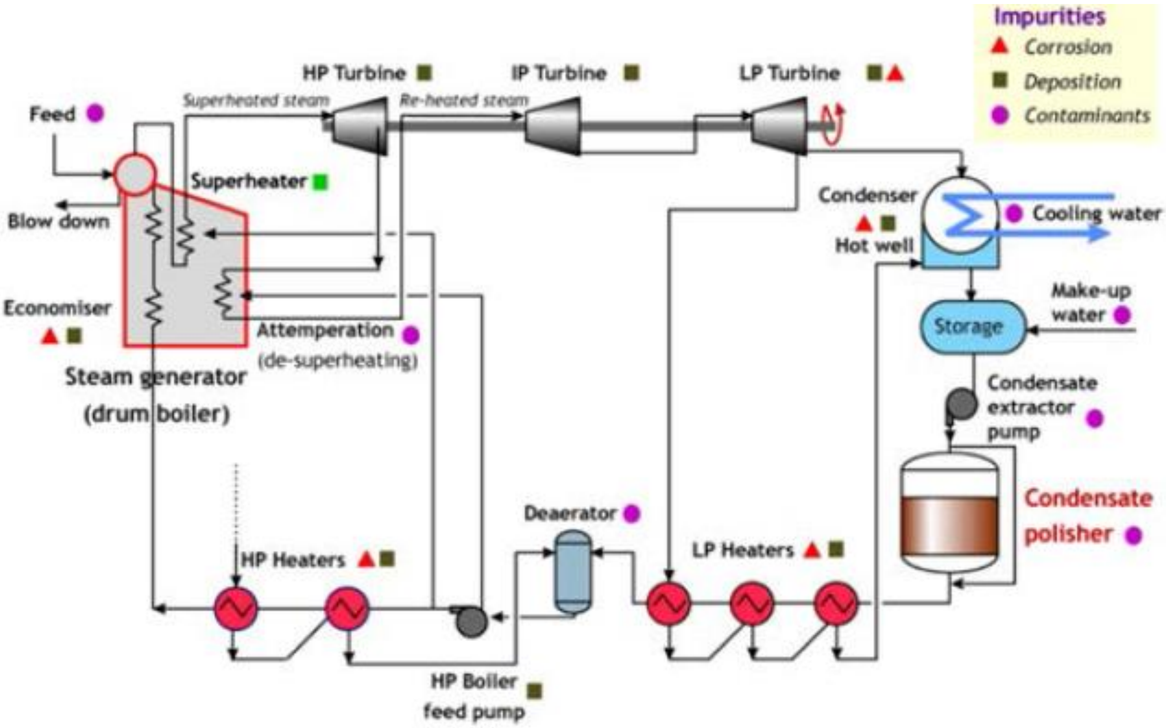


Figure 15: Location of a typical CPP plant in a power plant [59]

There are different types of CPP plants that maybe utilised to remove contaminate and achieve condensate within acceptable chemistry limits. These include particle filtration, deep-bed condensate polishing, and powdered-resin filter/demineralisation. All these methods will require the resin regeneration upon exhaustion making it a water consumer similar to that of the Demin plant.

By analysing the various processes within the WTP, several effluent streams exist. The various treatment processes requiring the addition of chemicals, in the pursuit of improving the water quality within the pre-treatment plants, produce large quantities of sludge which is then discharged to waste dumps in the form of slurry. The Demin and CPP plant produces effluent, which can be either very acidic or alkaline, that gets disposed of in suitable waste sites. These waste water streams are therefore considered to be sinks as they are consumed by the process and can only be recovered back through additional treatment processes [60].

2.8 Cooling water systems

The CW system in a wet-cooled coal-fired power plant is the main contributor towards high raw water consumption [70]. This is attributed to the waste heat rejected via CW systems which use cooling water as a make-up source [7]. The quantities of water evaporated through open evaporative cooling towers are dependent on the efficiency and generated power from the energy conversion process.

Eskom power plants uses either wet-cooled systems (evaporative) or dry-cooled systems. Dry-cooled systems use air as the cooling medium instead of cooling water, which significantly reduces the raw water consumption of the power plants. Dry-cooled power plants have annual water consumption in the range of 0.3L/kWh to 0.5L/kWh during normal operation which is inclusive of all water consuming processes [71]. Whereas, wet-cooled power plants experience water performance in the range of 1.5L/kWh to 2.5L/kWh. According to Kröger [71], a fossil fuel fired power plant with 40% efficiency, will reject approximately 40% of the heat produced through the CW system [71]. For a typical 600MW coal-fired power plant that operates at 70% capacity factor, this would require between $5x10^6$ m^3 and $10x10^6$ m^3 of raw water make-up water annually due to cooling water evaporation, inclusive of windage and drift losses, through the cooling tower. Thus, a thorough understanding of the evaporation losses in wet-cooled power plants is crucial in trying to reduce Eskom's water footprint, as well as to protect the water sources of the country.

As illustrated in Figure 16, water is lost in a wet cooling tower through evaporation, windage and drift losses, and blowdowns [70]. Evaporation losses are directly related to the required heat rejection from the Rankine cycle [7]. Windage and drift refer to the amount of water lost in the form of mist due to entrained water droplets in the flow of air to the atmosphere [72]. Blowdowns are needed to ensure the concentration of chemicals in the water system does not exceed certain chemistry limits [73].

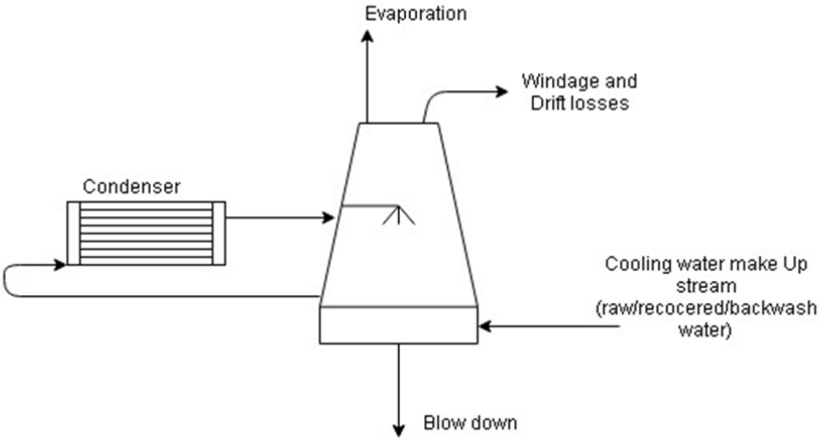


Figure 16: Typical schematic of a cooling tower water balance

2.8.1 Evaporation loss

In power plants, exhaust steam condenses, using surface condensers, where heat is rejected to the circulating cooling water (CCW) via condenser tubes. Power plants make use of cooling towers for cooling purposes [70]. A cooling tower uses a combination of heat and mass transfer to cool water [71]. The heated water entering the cooling tower via CW ducts is distributed in the tower by spray nozzles and fill packing in order to increase the surface area to the atmospheric air as depicted in Figure 17 [74].

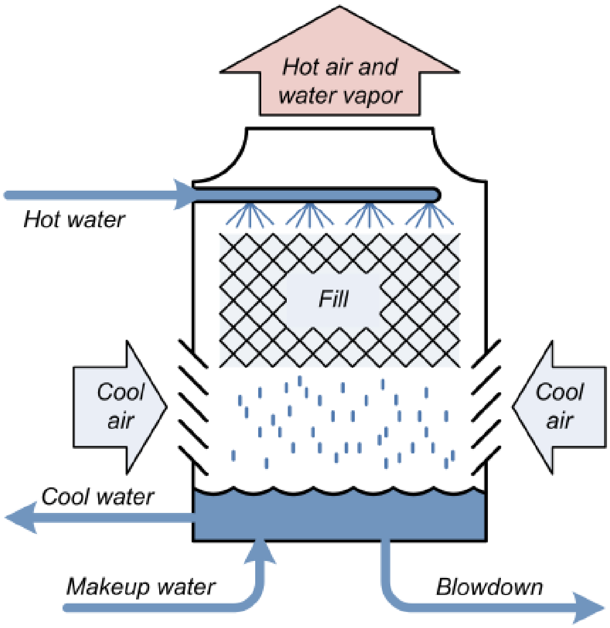


Figure 17: Cooling tower operation in a power plant [4]

The flow of air can be achieved by either a mechanical draught (produced by fans) or natural draught [71]. A portion of water entering the tower is evaporated due to the moisture content of the air being less than saturated at the temperature of the water. The process of evaporation requires energy for the phase change from liquid to vapour, resulting in the cooling of the water stream. Hence, the heat transfer in cooling towers occurs by both sensible heat from water to air (convection) and the transfer of latent heat by the evaporation of water (diffusion) [73]. Approximately 1% to 3% of the CCW flow is evaporated through the cooling tower [71]. This results in the cooling process of the water. The cooled water is stored in a water basin and pumped back to the condenser.

The type of CW system considered in this dissertation is that of a natural draft wet cooling tower as shown in Figure 17. The air flow in a natural draft cooling tower is created by the difference in density between the heated humidified air inside the tower and the heavier ambient air external of the tower [71].

Cooling tower evaporation fundamental principles

Cooling tower calculations require the understanding of psychometric studies [75]. This is due to atmospheric air consisting of a mixture of air and water vapour. Pure substances, such as water, exist as a liquid at a given pressure and low temperatures; however, as the liquid is heated and the temperature rises, the liquid will start to evaporate at a specific temperature, known as the saturation temperature, for the corresponding pressure. Vapour pressure is referred to as the pressure that corresponds to that specific temperature [75]. Thermodynamic properties can be obtained from psychometric charts or steam tables where usually two independent properties are required to determine all other thermodynamic properties of the fluid.

The fundamental principle of the cooling tower operation is that of evaporative cooling, where ambient air is humidified and warm water is cooled due to heat and mass transfer interactions between them [76]. The temperature difference between the ambient air and the water is the driving force for the heat transfer, whereas the vapour pressure is the driving force for mass transfer [76]. As air rises through the tower, it receives the latent heat of vaporisation from the warm water stream flowing down, and is cooled [77]. This process results in the humidity level of the air stream increasing to almost saturation conditions as it flows upwards [77].

A frequently used theory to evaluate the thermal performance of cooling towers is called the Merkel method [78]. The driving force in the Merkel equation is the difference between the enthalpy of saturated air at the water temperature, and the enthalpy of air at the air temperature [73]. The heat transfer between the warm water and cooler surrounding air is represented in Figure 18 [79]. The values for H_s is the enthalpy of saturated air at the water temperature and H_a is the enthalpy of the air stream. The vertical line ($H_s – H_a$) shows the enthalpy driving force.

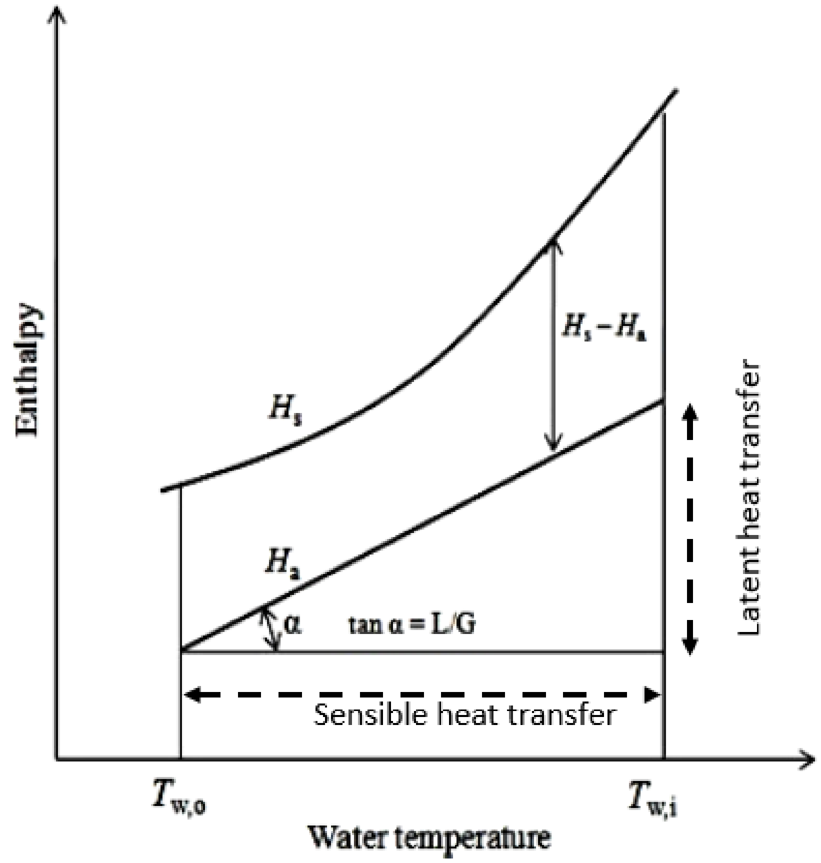


Figure 18: Cooling tower enthalpy and water temperature diagram [79]

This section of the dissertation will focus more on the methods for calculating the water evaporated during the cooling process. One of the assumptions in the Merkel equation is that water due to evaporation in the energy balance can be neglected [78]. By employing the Merkel method, the mass flow rate of the evaporated water can be estimated [78]. The mass balance in equation (9) indicates the evaporation of water is equal to the difference in moisture content of the air across the tower [77].

$$\dot{m}_{evap} = \dot{m}_{air} \cdot (w_{in} - w_{out}) \tag{9}$$

Where:

$\dot{m}_{evap}$ = mass flowrate of water evaporated through the cooling tower (kg/s)

$\dot{m}_{air}$ = mass flowrate of dry air flow (which remains the same at the inlet and outlet air streams) (kg/s)

w = absolute humidity, kg water/kg dry air/s. The subscripts “in” and “out” refer to the entry and exit locations of the tower

Hence, to calculate the water evaporation using these fundamental principles, the air conditions are required.

Simplified form to calculate cooling tower evaporation

A cooling tower is designed to remove the total heat load extracted from the plant by reducing the warm water temperature. The performance of cooling towers are usually expressed in terms of the parameters range and approach [80]. The approach of the cooling tower is different when considering the outlet water temperature and the wet-bulb temperature of the air [80]. This is measured when evaluating the maximum cooling possible, as the cooling water temperature cannot be cooled below the wet-bulb temperature [77]. The cooling range is defined as the difference between the inlet and outlet water temperatures [77].

The calculation of the airflow is complex and air conditions are not usually measured values. This resulted in the establishment of a common rule of thumb for cooling tower evaporation. This rule states that for every 10^{o}F (5.5^{o}C) drop in water temperature, approximately 1% total mass flow of water is lost due to evaporation [73]. The simplified evaporation rate can be calculated using equation (10).

$$\dot{m}_{evap} = \frac{1\%}{10^{\circ} F} \cdot \Delta T \cdot \dot{m}_{CW} \cdot f_{sensible} \tag{10}$$

Where:

ΔT = water temperature difference between the tower inlet and the water basin outlet (°C), also known as the cooling tower range.

$\dot{m}_{CW}$ = mass flowrate of circulating cooling water (kg/s).

$f_{sensible}$ = correction factor used to account for sensible heat transfer

This empirical equation is the most widely used approximation for cooling tower evaporation. Figure 18 above depicts the latent heat transfer due to a portion of water vaporising, and the sensible heat transfer due to the difference in temperature of the water and air. The fraction of heat load rejected through sensible heat transfer is denoted as, $f_{sensible}$, in equation (10) .

The sensible heat correction factor can be used to account for sensible heat transfer and ranges between the values 0.65 and 0.85 [81]. This factor depends on cooling tower design and the humidity of the air entering the tower, and is therefore not a constant value [4]. Cooling tower evaporation can also be defined in terms of the heat load rejected.

The heat load for cooling water can be represented by equation (11) when assuming all evaporation is due to an evaporative cooling mechanism.

$$\dot{m}_{evap} = \frac{\dot{Q}_{cw}}{h_{fg}} = \frac{\dot{m}_{CW} \cdot \Delta T \cdot c_{p.water}}{h_{fg}} \tag{11}$$

Where:

$c_{p.water}$ = specific heat of water at atmospheric pressure = 4.184 kJ/ (kg.K)

h_{fg} = change of phase enthalpy (kJ/kJ) or latent heat of vaporisation

$\dot{Q}_{cw}$ = heat rejection from the Rankine cycle to the cooling water (MW)

If the sensible heat factor is defined as one in equation (10) implying that the heat transfer is through latent heat of vaporisation, then the empirical equation (10) is merely a numeric approximation of the energy balance equation (11). Hence, the sensible factor is necessary in adjusting the cooling tower evaporation and improving the final evaporation output value. The factor is considered lower in winter conditions and higher in summer conditions [81]. It is approximated that 80% of heat transfer is due to latent heat and 20% is due to sensible heat [75].

A potentially more accurate alternative is to make a reasonable assumption for the exit air condition, which will enable one to use equation (9). A good approximation of the outlet air dry-bulb temperature can be taken as the average of the inlet and outlet water temperature [73]. Assuming that the outlet air is fully saturated, the outlet enthalpy and absolute humidity can be retrieved from a psychometric chart.

The only additional unknown is the air mass flow. The energy balance around the cooling tower states that the amount of heat lost by water is equal to the enthalpy rise in the air [79] as seen in equation (12) below.

$$\dot{m}_{CW} \cdot \Delta T \cdot c_{p.water} = \Delta \mathrm{H_a} \cdot \dot{m}_{air} \tag{12}$$

Where:

$\Delta \mathrm{H_a}$ = difference in enthalpy of inlet air at wet-bulb temperature and the exit air at saturation conditions (kJ/kg)

Figure 18 shows that the slope of the air operating line can be calculated as the flow rate of water to the flow rate of air, and is known as the L/G ratio. The L/G ratio is calculated from equation (12). Combining this with equation (9), the evaporation rate can be calculated by equation (13).

$$\dot{m}_{evap} = \frac{\dot{m}_{CW}}{\left(\dfrac{\Delta \mathrm{H_a}}{\Delta T \cdot c_{p.water}}\right)} (w_{in} - w_{out}) \tag{13}$$

The application of equation (13) requires the cooling water flow rate and temperatures, as well as the air inlet conditions, which can be obtained from a power plant weather station. This provides a more practical approximation for calculating cooling tower evaporation at power plants.

Eskom cooling tower evaporation calculation approach

Eskom CW systems are designed such that they are common systems. This implies that the cooling water system is shared between multiple power generating units. The cooling water exiting all of the cooling towers flow to a common water well from where it is then distributed to the various station units by common ducts. It should be noted that there are no CW flow measurements available and temperature measurements are only available at the condenser inlet and outlet of each unit. By using the overall plant performance with the combined overall cooling tower performance when performing evaporation loss calculations on the entire power plant, Eskom has developed its own approach of calculating the cooling tower evaporation losses.

Eskom conducted acceptance tests on a cooling tower to assess performance and assumed this applicable to all other towers for the same tower design. The cooling tower evaporation was calculated and reported as a function of load production (Ml/GWh). The evaporation rate values for each plant can be obtained from acceptance test reports or OEM (Original Equipment Manufacturer) manuals. Using the design evaporation loss and the SSO energy (GWh), the volume of water evaporated, theoretically, can be estimated from equation (14).

$$v_E = E_{SSO} \cdot I_E \tag{14}$$

Where:

I_E = design cooling tower evaporation per station sent out energy (Ml/GWh)

v_E = design volume of water lost from cooling tower evaporation (Ml)

E_{SSO} = cumulative net energy output from the power plant (GWh) or SSO energy

The cooling tower evaporation adjustment factor, v_{cf} which is used for thermal efficiency correction in Eskom is given by equation (15).

$$v_{cf} = (\eta_d - \eta_a) \cdot E_{sso} \cdot 0.04 \frac{L}{kWh} \tag{15}$$

Where:

v_{cf} = cooling tower evaporation adjustment factor for overall station thermal efficiency (L)

η_d = overall station thermal efficiency evaluated at design conditions (0 – 100)

η_a = overall station thermal efficiency evaluated at actual conditions (0 – 100)

The calibration factor for efficiency in equation (15) is 0.04L/kWh. This was based on tests conducted to establish correction factors for changes in thermal efficiency in Eskom power plants. Since the evaporation through the tower is impacted by the power plant overall thermal efficiency, Eskom uses equation (15) to calculate deviations from design.

2.8.2 Windage losses

There also exist windage losses from the tower; however this is relatively small in Eskom power plants as they have adopted the use of drift eliminators as part of the cooling tower designs to reduce windage losses.

Using the Eskom test results for windage losses and the SSO energy, the volume loss of windage can be established by equation (16) below.

$$v_D = E_{sso} \cdot I_D \tag{16}$$

Where:

v_D = design volume of water lost from cooling tower via windage and drift losses (Ml)

I_D = design cooling tower drift and windage loss (Ml/GWh)

The drift losses can be assumed from 0.002% to 0.2 % of the total volume CCW flowrate ($\dot{v}_{CW}$) where design losses, as used in equation (16), are not available from the manufacturer [82]. From large-scale industrial cooling towers, in the absence of manufacturer's data, it may be assumed to be [83]:

$\dot{v}_D$ = 0.3% to 1.0 % of $\dot{v}_{CW}$ for a natural draft cooling tower without windage drift eliminators

$\dot{v}_D$ = 0.1% to 0.3 % of $\dot{v}_{CW}$ for an induced draft cooling tower without windage drift eliminators

$\dot{v}_D$ = about 0.005 % of $\dot{v}_{CW}$ (or less) if the cooling tower has windage drift eliminators

$\dot{v}_D$ = about 0.0005 % of $\dot{v}_{CW}$ (or less) if the cooling tower has windage drift eliminators and uses sea water as make-up water.

2.8.3 Blowdown losses

The process of evaporation requires frequent dumping of cooling water, which is referred to as blowdowns. The CW blowdown process is a requirement to remove the accumulation of dissolved solids from the CW stream via clarification [73]. There are various chemical species in the CW system which concentrates over time because of evaporation. This is combined with the ingress of salts via the water make-up stream. The number of times a chemical species can concentrate in the CW stream and still comply with the chemistry standards, is defined as the COC for that species.

The COC is calculated as the ratio of dissolved solids in the CW to that of the same dissolved solids in the make-up stream [71]. The chemical species with the lowest COC is defined as the limiting parameter as it is likely to exceed the chemistry limit first. For example, if the silica concentration in the make-up stream is 6mg/L and the limitation of silica is 150mg/L, then the COC limit is (150/6) which indicates a COC for silica of 25. The derivation of the COC for a system will be described later on by equation (21) and equation (22) for further explanation. The number of blowdowns required is determined by the limiting COC chemical species in order to comply with the chemistry limitations.

Most power plants perform CW treatment by means of lime or soda ash dosing. Acid dosing can also be implemented where lime plants are unavailable in order to maintain the CW chemistry within specification. However, acid dosing is not the preferred method of treatment due to the introduction of sulphates into the system. Lime or soda ash dosing is the main pre-treatment method for cooling water treatment [60].

One way to reduce water consumption is to reduce the number of blowdowns from the CW system which requires an increase in the COC [10]. The raw water quality plays a crucial role in the COC value for a system as it is constantly introducing new salts into the system at varying concentrations. The COC value can be extremely low if make-up water sources have high contaminates resulting in high raw water consumption. Figure 19 illustrates the inverse relationship between the volume flow rate of blowdown water and the COC of the cooling water [84]. The make-up water flowrate is highly sensitive to the water quality of both the CW and raw water make-up sources.

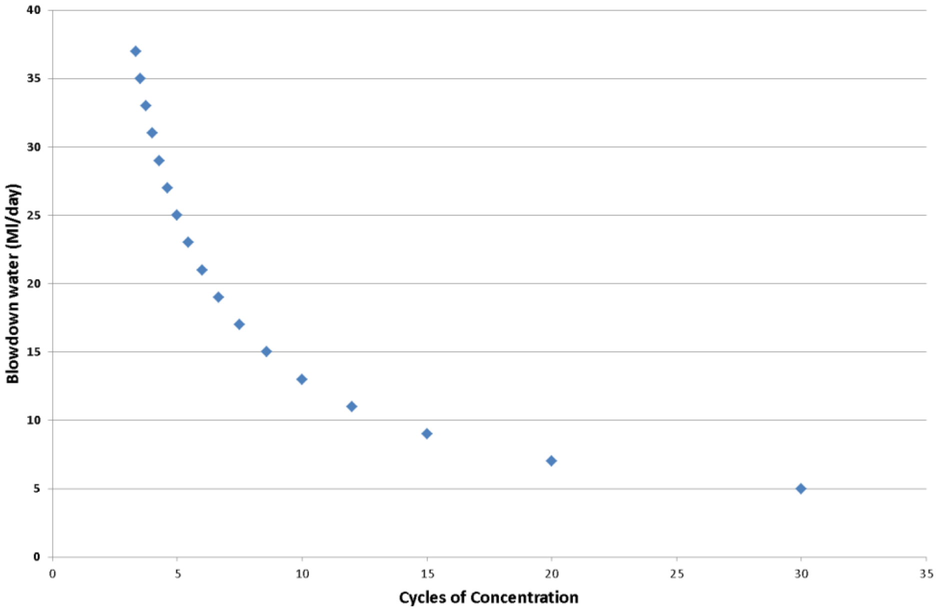


Figure 19: Relationship between CW COC and blowdown flowrate [25]

The CW make-up can consist of other recovery streams and is not always just the raw water make-up. These can be either recovered ash water from the ash dams, treated sewage water, or backwash water from the potable and Demin sand filter process. If the water chemistry of the additional water source is suitable for recovery, it can assist in reducing the raw water make-up required. This results in an improvement of the overall water consumption by the power plant. The recovery process is managed via Eskom procedures to ensure chemistry compliance at all times [60].

A set of volume flow balances are used to calculate the COC for the cooling water system as well as the volume of blowdown water. The water flow balance of the cooling system is defined by equation (17) [84].

$$\dot{v}_M = \dot{v}_E + \dot{v}_{BD} + \dot{v}_D \tag{17}$$

Where:

$\dot{v}_M$ = make-up water (m^3/h)

$\dot{v}_{BD}$ = blowdown (m^3/h)

$\dot{v}_E$ = evaporated water (m^3/h)

$\dot{v}_D$ = drift and windage loss of water (m^3/h)

Since the cooling tower evaporated water contains no salts, it allows for a mass balance around the system as depicted in equation (18):

$$\dot{v}_M \cdot C_{M,i} = \dot{v}_E \cdot C_{E,i} + \dot{v}_{BD} \cdot C_{BD,i} + \dot{v}_D \cdot C_{D,i} \tag{18}$$

$$C_{E,i} = 0$$

$$C_{D,i} = C_{BD,i} \tag{19}$$

Where:

$C_{M,i}$ = concentration of the chemical constituent (*i*) in the make-up water (ppm)

$C_{E,i}$ = concentration of the chemical constituent (*i*) in evaporated water (ppm)

$C_{BD,i}$ = concentration of the chemical constituent (*i*) in the blowdown water (ppm)

$C_{D,i}$ = concentration of the chemical constituent (*i*) in the drift water (ppm) which is the same as the circulating water

By substituting equation (18) and equation (19) into equation (17), the following expression can be derived:

$$\dot{v}_M \cdot C_{M,i} = C_{BD,i}\left(\dot{v}_{BD} + \dot{v}_D\right) \tag{20}$$

The COC of the CW system can thus be expressed by equation (21) and equation (22) [85].

$$N_i = \frac{C_{BD,i}}{C_{M,i}} \tag{21}$$

$$N = \frac{C_{Limit,i}}{C_{M,i}} \tag{22}$$

Where:

N_i = COC of constituent (*i*)

N = COC based on the limiting parameter

$C_{Limit,i}$ = water quality limit for constituent (*i*) (mg/L)

The blowdown water from the cooling tower is calculated by substituting equation (21) into equation (20) and is given by equation (23) [84]:

$$\dot{v}_{BD} = \frac{\dot{v}_E}{N-1} - \dot{v}_D \tag{23}$$

The COC calculation for ion pair limits differs in the following way:

$$N = \sqrt{\frac{C_{Limit,ij}}{C_{M,i} \cdot C_{M,j}}} \tag{24}$$

Where:

$C_{Limit,ij}$ = water quality limit of constituent (*i*) and (*j*)

$C_{M,i}$ = water quality limit of constituent (*i*) in the make-up stream

$C_{M,j}$ = water quality limit of constituent (*j*) in the make-up stream

When calculating the blowdown water loss, often the drift losses are negligible and assumed to be zero allowing for simplification of equation [84] (23).

$$\dot{v}_{BD} = \frac{\dot{v}_E}{N-1} \tag{25}$$

Thus, if the cooling tower evaporation and raw water quality are known, the theoretical CW clarifier blowdown can be calculated [86].

2.9 Ash plant and drainage systems

Ash is fundamentally an inorganic fraction of coal that does not burn during the combustion process in the boiler [2]. Ash comprises primarily of oxidised materials such as silica, aluminium oxide, calcium oxide, titanium dioxide, sulphur trioxide, and magnesium oxide, as well as several heavy metals. The ash content of the coal and the efficiency of the power plant determine the amount of ash produced out of the boiler [2]. The ash content can vary from as little as 20% to in excess of 35 %. Ash is relatively inert and is commonly used by power plants as an effluent sink.

The process of coal combustion produces both bottom and fly ash [87]. Bottom ash, which accounts for 10% to 20% of the total ash produced [87], is the heaviest type of ash, and collects in the bottom of the boiler, from which it is removed for disposal [2]. Bottom ash is collected in an ash sump. Fly ash, which makes up the balance of the ash, is a lighter fraction, and is carried along with the flue gases from the boiler. Fly ash is removed using electrostatic precipitators or fabric bag filters.

Bottom ash is pumped to the ash dam from an ash sump, while fly ash is conveyed via separate sluice pumps to the ash dams. The ash conveyed to the ash dams form the ash dam walls. The water collected in the ash dam is recycled in a closed loop via ash pumps for ashing processes (wet ash system).

The proportions of bottom ash to fly ash depend on the type of mill employed and coal composition of the plant. The purpose of the milling plant is to both dry and pulverise the raw coal feed to a specified particle size required for the combustion process [88]. The industrial norm for pulverised fuel (PF) fineness is such that at least 80% by weight of the PF should not exceed 75um particle size [89].

Eskom power plants make use of Vertical Spindle and Tube mills where the grinding mediums are either rollers or balls. The type of mill can be classified as either a roller mill or ball mill. Eskom mills are designed such that ball mills produce roughly 80% bottom (coarse) ash and 20% fly ash, while Tube mills produce 10% bottom ash and 90% fly ash [61]. The ratio of bottom to fly ash is verified during the boiler acceptance test and can be used as a more accurate data source when performing calculations [90].

The recovery of ash water into the CW system depends on the quality of the ash water, mainly the concentration of sulphates, and the CW water chemistry. The concentration of hydroxides in the ash water is used to determine the sulphate concentration [57]. If the concentration of hydroxides (pH) is high, the solubility of aluminium from the ash will increase forming aluminium hydroxide. An insoluble salt known as Ettringite can also be formed. Ettringite removes calcium and sulphate from the ash water. The formation of Ettringite is driven by the pH of the ash water. Maintaining an optimum concentration of hydroxides in the ash water allows for recovery of ash water in the CW system [57]. This is an important process adopted by power plants to reduce raw water intake.

2.9.1 Wet ash systems

Wet ash systems are more water intensive than dry ash systems [2]. This is due to large quantities of water used to sluice ash from the bottom of the boiler to the final effluent disposal site, usually the ash dams. The bottom ash leaves the boiler at a high temperature and requires cooling prior to further handling. This is achieved by quenching it with water from the ash dams. As the hot ash is released from the boiler, it falls into cold water contained in the ash hopper. A portion of this water is evaporated and lost to the atmosphere through the boiler flues. The balance of the quenching water is incorporated into the ash. Bottom ash quenching is an unavoidable loss, whether plants employ wet or dry ash handling systems. The amount of design water required as make-up due to ash quenching can be found in OEM design manuals. Eskom has established a ratio of water evaporated due to quenching and the mass of bottom ash production, known as the quenching factor. This accounts for varying load and coal quality scenarios.

The quenching factor can be established by performing the mass and energy balance principles. However, certain assumptions have been made to avoid computational complexity. Figure 20 depicts the boundary conditions used for the mass and energy calculations on the ash hopper.

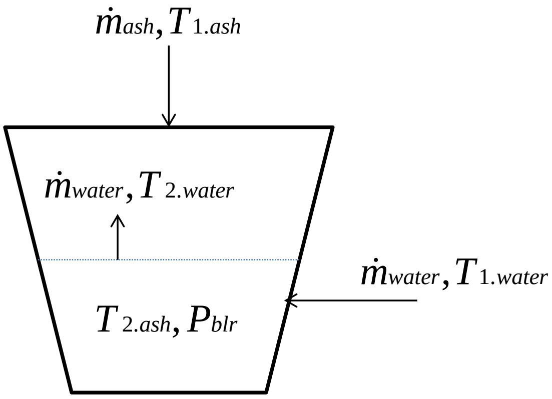


Figure 20: Boiler bottom ash quenching schematic

The assumptions made for the quenching factor calculation include:

- Make-up flows remain constant at ambient water temperature $T_{1.water}$ = 20°C, and vaporises at $T_{2.water}$ = 100°C.
- Ash temperature entering the hopper is assumed based on boiler operation at $T_{1.ash}$, which can be approximated at 950°C and ends up at temperature $T_{2.ash}$, which is assumed an average temperature of $T_{1.water}$ and $T_{2.water}$. An energy balance over the system can be performed to obtain $T_{2.ash}$, however, insufficient thermal properties of ash were available to conduct this analysis.
- Temperature rise of water in hopper is negligible and therefore assumed constant over time.
- Level control maintains a set water level in the hopper.
- The enthalpy of vaporisation, h_{fg} ,is taken at boiler furnace pressure and saturated vapour conditions.

The overall quenching factor calculation is explained by equation (26). This was achieved by performing an energy balance that assumed the energy lost by the ash, Q_{ash} ,is gained by the water as Q_{water}.

$$Q_{water} = \dot{m}_{water} \cdot c_{p.water} \left(T_{2.water} - T_{1.water}\right) + \dot{m}_{water} \cdot h_{fg}$$

$$Q_{ash} = \dot{m}_{coarse.ash} \cdot c_{p.ash} \cdot \left(T_{2.ash} - T_{1.ash}\right)$$

$$f_q = \frac{\dot{m}_{water}}{\dot{m}_{coarse.ash}} = \frac{c_{p.ash}\left(T_{2.ash} - T_{1.ash}\right)}{c_{p.water} \cdot \left(T_{2.water} - T_{1.water}\right) + h_{fg}} \tag{26}$$

Of the total water conveyed to the ash dam, a portion of this water is recycled back to the ash plant while the rest is absorbed by ash itself due to its absorption properties. The percentage of water retention within the ash is known as Ash Interstitial Hold (AIH). This was established experimentally for Eskom power plants as approximately 60%. This was confirmed by calculating the run-off factor (explained in Section 2.9.2) for the ash dam of 40%.

The ash slurry, conveyed from the power plant, is discharged into the ash dam where the bottom ash is used to build ash dam walls. The remaining slurry forms pools of water on the ash dam. The pools contain penstocks to allow for decanting of the water into another storage dam for the next cycle of ashing. The dumping of ash on the ash dams, result in an increase in height of the dam due to the accumulation of ash. The ash dam rise can be estimated by using equation (27). This equation is used by Eskom to monitor the height increase of the dam per annum.

$$h_{ash} = \frac{v_{ash}}{A_{ash\_active}} \tag{27}$$

Where:

h_{ash} = rise of an ash dam (m)

v_{ash} = volume of ash accumulated on the ash dam (m^3)

A_{ash_active} = active surface area of the ash dam (m^2)

It must be appreciated that while most of the ash dam water is recovered, significant losses occur [13]. This entails evaporation losses due to the large surface area of the wet ash, and that of pools of water that forms on the surface of the ash dam. These pools form because of solid particles that separate from the ash water. Water is also lost due to the absorption of water in the ash and seepage of the ash dam. Figure 21 depicts the overall water flow network for the ash and drainage system.

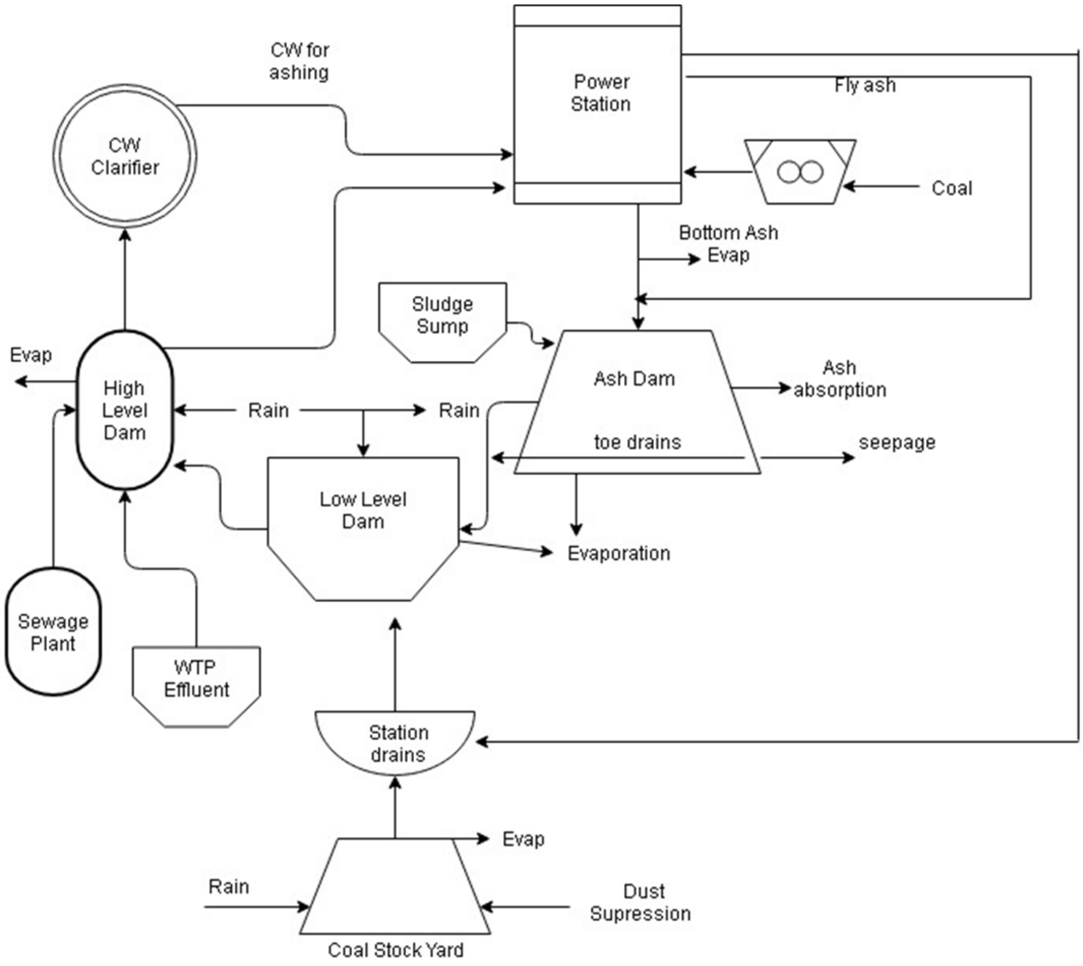


Figure 21: Ash plant and drainage system

Water loss from the ash system indicated in Figure 21 occurs mainly due to the properties listed below:

- Ash Interstitial Hold (absorption on the ash)
- Evaporation from the wet ash on the ash dam
- Evaporation from the water pools formed on top of the ash dam
- Evaporation during the quenching of bottom (coarse) ash
- Seepage from the ash dam
- Bottom ash evaporation during quenching

2.9.2 Drainage systems

Power plants are designed with drainage systems (station drains) that exists as concrete channels to collect storm water and drainage water from the power plant. Drainage systems are designed to handle a one in fifty-year storm as the worst case scenario [91]. The drains at the power plants collect water from the CW system drains and/or overflows, storm water channels, Demin drainage from the plant (condensers, boilers, leaking valves, etc.), CSY drains, and potable water from floor washing. Water collected via the station drains are diverted to either clean water dams or ash dams.

Run-off is the term used for the total amount of water from precipitation flowing into a catchment area [92]. The storm water drainage flow is a function of the run-off factors and catchment area. The run-off factors can be determined from literature [93].

The run-off is heavily dependent on the catchment slope and shape, the type of soil, and the rainfall received in the area [92]. The peak flow is obtained from the relationship depicted by equation (28) using the rational method [93].

$$\dot{v}_r = f_r \cdot i \cdot A \tag{28}$$

Where:

$\dot{v}_r$ = peak run-off water flow rate (m^3/h)

f_r = run-off coefficient

i = average intensity rainfall (m/h)

A = watershed area (m^2)

There are different methods that can be used to calculate the run-off coefficient. The Rational method used in Eskom is based on a simplified representation of the law of conservation of mass with rainfall intensity as the main input. The run-off coefficient represents the portion of the storm rainfall at the outlet of the catchment area. The accuracy of the run-off coefficient is dependent on the experience and engineering judgement applied. The values for the average rainfall in various catchments are well documented and easily accessible for water balance calculations [93].

The run-off coefficient can be calculated using equation (29):

$$f_r = f_1 + f_2 + f_3 \tag{29}$$

Where:

f_1 = run-off coefficient according to average catchment slope

f_2 = run-off coefficient according to average soil permeability

f_3 = run-off coefficient according to average vegetable growth

Values for the factors in equation (29) are obtained from Table 6.

Table 6: Recommended values of run-off factors to use in the rational method for average annual precipitation of < 600mm [93]

Component	**Classification**	**Run-off factor**
Surface and slope (f_1)	Wetlands < 3% Flat areas (3 -10%) Hilly (10 – 30%) Steep slopes (> 30%)	1% 6% 12% 22%
Strata permeability (f_2)	Totally permeable Permeable Semi – permeable Non permeable	3% 6% 12% 21%
Vegetation (f_3)	Dense bush and plantations Sparse bush and fields Grasslands No vegetation	3% 7% 17% 26%

Figure 22 depicts the station drain layout and the direction of surface water run-off. It is important to understand the concept of run-off water and how this is established when performing a water balance. Run-off water is generated within a catchment area due to rainfall, and depends on the storm characteristics, catchment response, and influence of the temporal storage of the run-off [93]. Topographical factors like the size, shape and slope of the catchment, soil type, geology, and vegetation, all dictate the catchment response. The developmental influences include land use, which can be classified either as rural or urban.

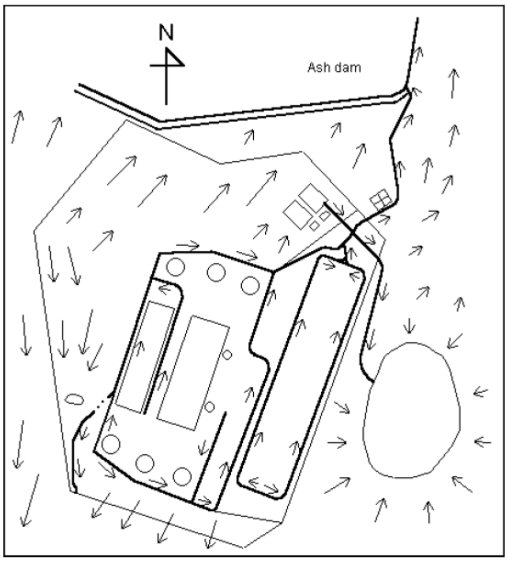


Figure 22: Station drainage layout and surface water run-off direction [91]

The station drainage flow can usually be determined by performing an overall water balance across the power plant and allocating the difference between the inlet and outlet to the station drains.

Water not consumed through evaporation and absorption, and which had not been discharged, must be on site in storage. Volume variance is the biggest contributor to varying consumption rates when performing a power plant water balance. Phreatic water (water contained in the ash) is difficult to quantify. Stage capacity curves for all storage facilities can be used to quantify the water stored in dams. However, this is heavily dependent on obtaining correct information on the area of the ash dam, as well as the rate of rise of the dam.

2.10 Effluent systems

The effluent systems consist of all waste streams that flow out of the power plant systems and are stored in the ash dams. These include the sludge water from the clarification process, effluent water from the Demin plant, and sewage water from the sewage plant. The effluent streams flow separately, and may be stored on different dams, depending on the effluent quality as depicted in Figure 21 . The design of sewage plants is based on the expected potable usage for domestic use [94]. Figure 23 illustrates the inflows and outflows of the sewage plant.

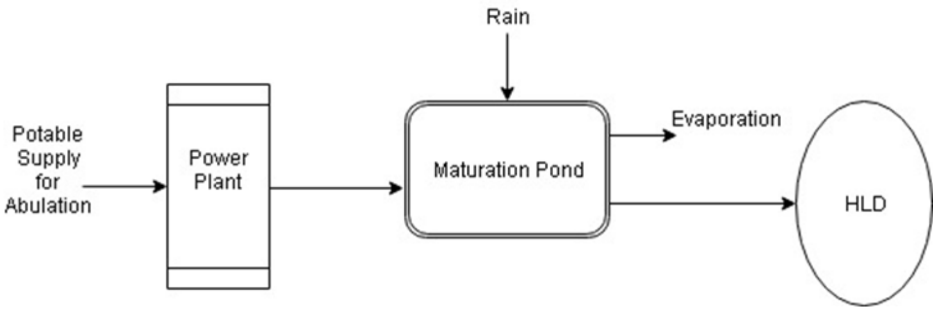


Figure 23: Sewage plant water balance

According to Eskom, 40% to 70% of the potable demand at the power plant will cascade to the sewage plant, while the remainder will be lost through the drains via floor washing and evaporation. This estimation is in line with figures reported by the Water Research Commission [94]. This is mainly due to the power plant supplying potable water to employee hostels outside the power plant. Potable water consumption can vary dramatically depending on third party supply and internal uses. Due to large variability in raw sewage and effluent flows, it is recommended that these streams be metered for accurate representation in water balance models.

2.11 Review of Eskom tools for water balance

Eskom has adopted the use of Microsoft Excel based tools for the development of water balance models and water performance calculations. Excel is a user-friendly tool and currently available to all users [19]. The approach adopted was sufficient when requiring once off analysis on a system with simple data transfers [19]. However, with plant deterioration on the increase and the loss of critical skills, the existing tools have proved insufficient in combating high water consumption.

Some of the challenges experienced with the existing Excel models are:

- The original water management tools were developed over 20 years ago without sufficient documentation on the methodology.
- Skills transfer was limited due to the lack of information available, and therefore the use of the water balance tools were limited to individuals.
- Changes made to the tools were not well documented and tracked, therefore difficult to manage revisions.
- References for the mathematical equations were not explained sufficiently.
- The tools were based on a predefined plant configuration, with fixed equations, making it difficult to amend for other power plants or where plant changes occurred.
- The tool was never set up for use when live data became available and for trending purposes

- Troubleshooting high water consumption became difficult without an interface with the cycle performance
- High number of manual inputs were required
- The model is heavily dependent on the availability of flow meter data

The next section will provide an overview of the existing water management tools and its setup and functionality.

2.11.1 Target setting tool

The Excel models were developed as site-specific models based on plant configuration. This resulted in several Excel models for different power plants. A single coal-fired wet-cooled power plant, illustrated in Figure 24, was selected as a case study based on the information available. This dictated the plant configuration that will be used going forward. The breakdown of the process equations is based on the latest Excel document for the selected power plant. The tool uses the design base conditions as inputs and the results are used to set the water consumption targets for the power plant.

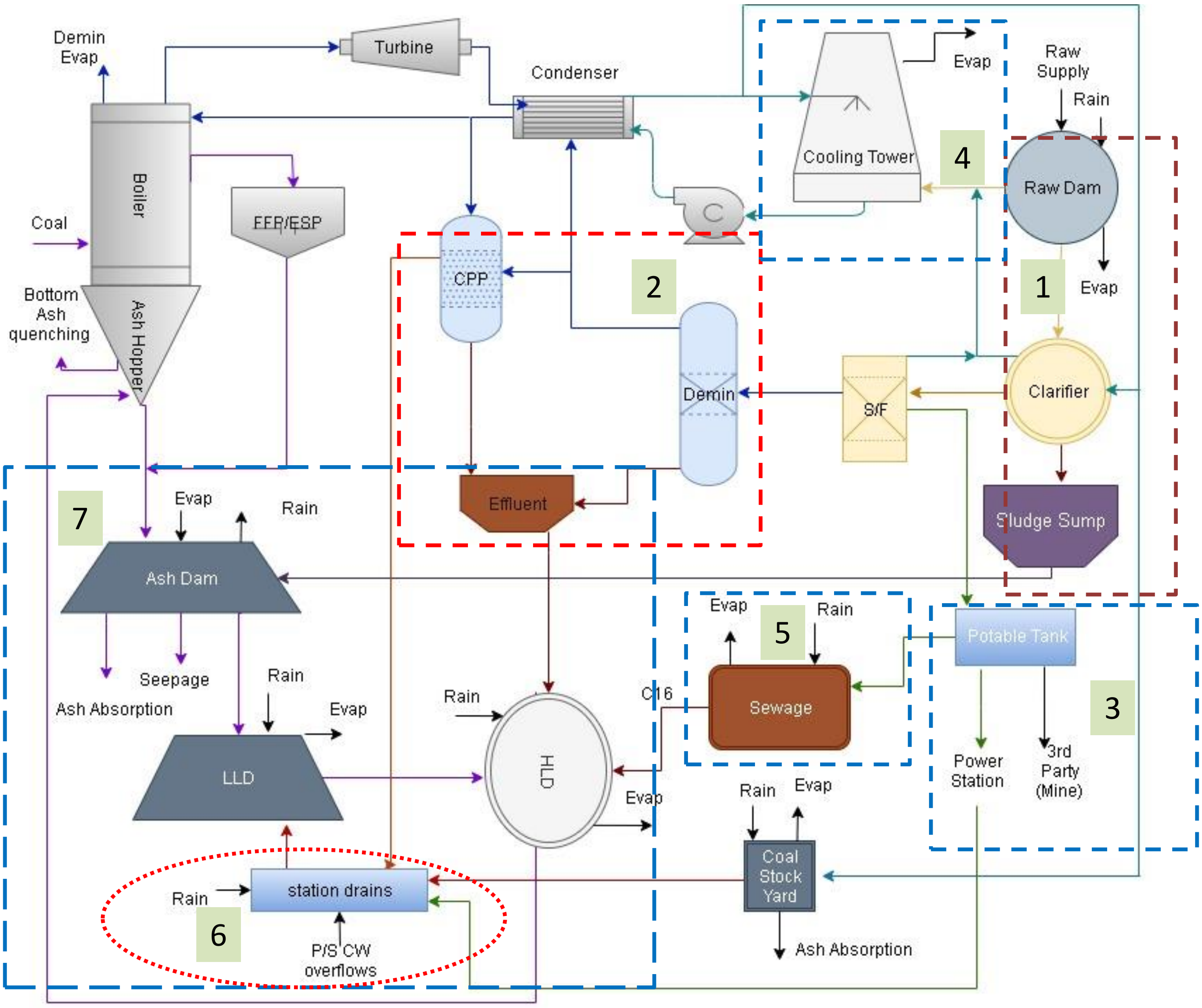


Figure 24: Overall water configuration for a wet-cooled power plant

Water performance / consumption targets are typically determined annually for each power plant, and then tracked monthly using available measurements. The approach adopted by Eskom for setting the targets is illustrated in Figure 25. The inputs required are based on the window period, plant performance, raw water and coal quality, climate conditions, and station dam and drainage areas, as well as design data for cooling water and Demin systems.

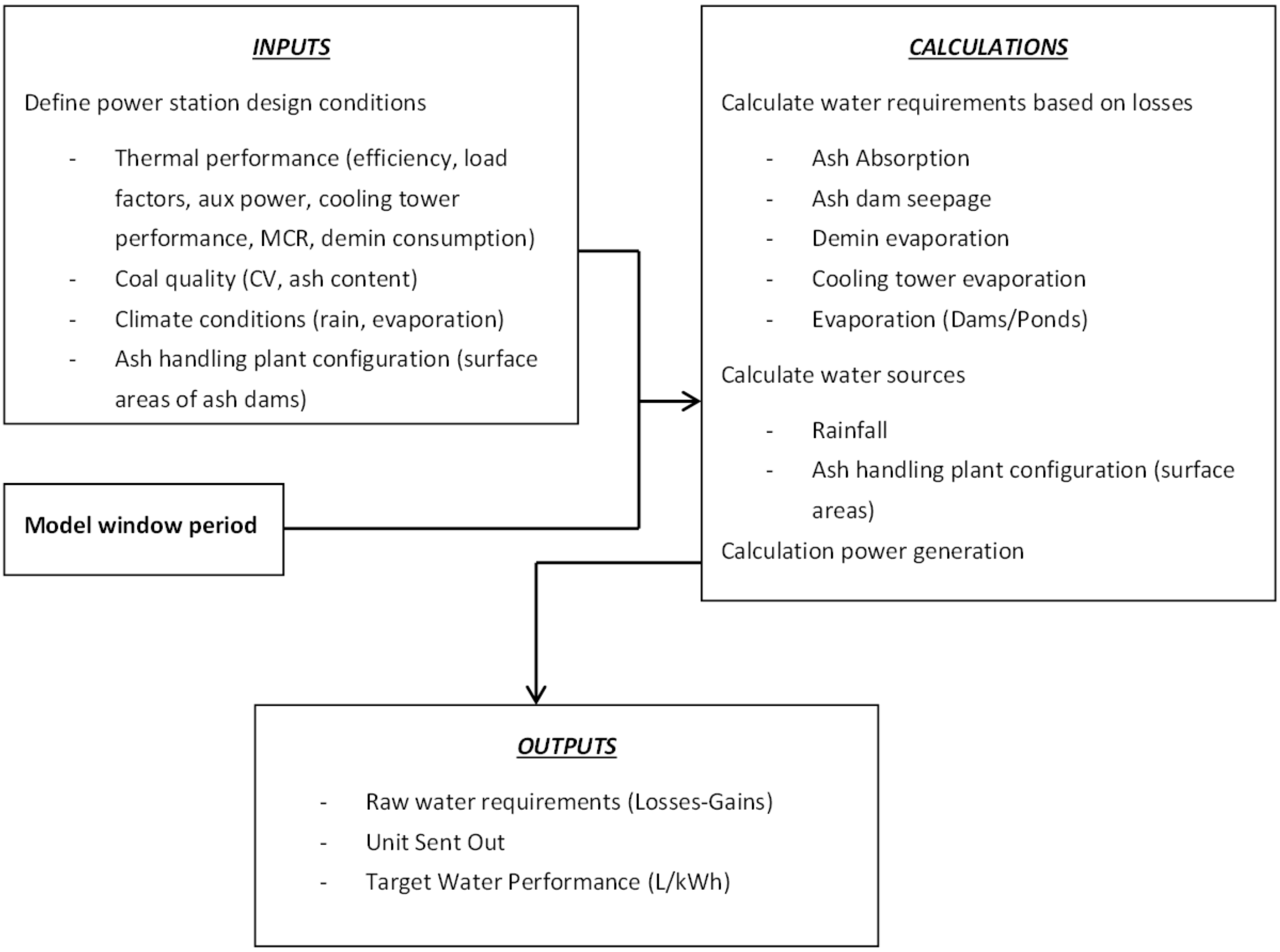


Figure 25: Eskom Excel model for target setting of water performance

The water performance of a power plant is expressed in terms of raw water consumed per station sent out energy (L/kWh) as defined by equation (30).

$$I_{raw} = \frac{v_{raw}}{\dot{W}_{net} \cdot t} \tag{30}$$

Where:

I_{raw} = water performance (L/kWh)

v_{raw} = volume of raw water consumed by the power plant (L)

t = operational time period (h)

The aim of the target tool was to establish the total raw water consumption for the specified period. The next section outlines the equations and sequence of calculations used to calculate the various flows in the water cycle. It must be noted that these calculations produce expected water consumption values based on the design assumptions and other inputs as shown in Figure 25.

The process calculates all the water losses on the power plant, as well as any gains due to rain or recovery as depicted in Figure 26.

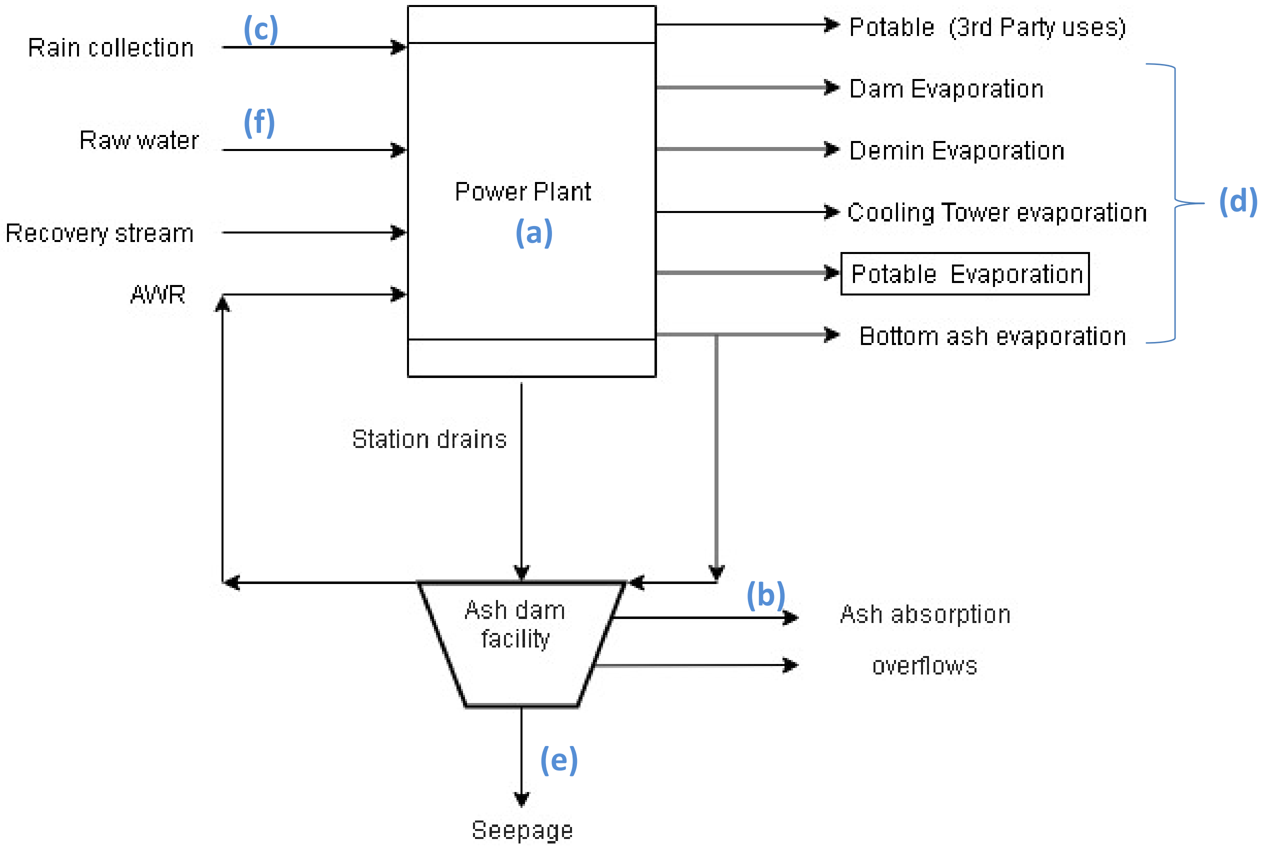


Figure 26: Power plant overview

The water losses shown in the image have been categorised into specific sections:

a. Evaporation (cooling tower, dams, bottom ash quenching and Demin)
b. Potable water for third party uses
c. Ash absorption (ash dams and CSY)
d. Ash dam seepage

The water gains has been categorised into specific sections:

e. Rain water collection (dams and run-offs)
f. Recovery streams (where applicable)

The water consumption of a power plant is mainly a function of the load generated, thermal cycle efficiency, coal and water quality, and climate conditions. The model was configured for a selected period, which was usually a month or a year depending on the need. This period is referred to as the window period and is inputted by the user at the start of the model. These key parameters form the basis of all the water management tools and are therefore, calculated at the start of the model.

a. Station Sent Out (SSO)

The design load generated is calculated using equation (3), with the Maximum Capacity Rating (MCR), design auxiliary power consumption, design load factor for the period specified, and the design number of operational units if the MCR is stated per unit. A power plant is built with a specific number of operational units with this number varying between sites. The net electrical output is used as the overall station sent out value for the water performance design calculation.

This calculation was used in the Excel model for the target case based on the target values set for the power plant for that specific year. Thus, the target SSO could be calculated by using the target load factor and number of operational units available in that year.

The need for this calculation in the Excel tool is to account for changes from the design SSO to the target SSO for the year. In an actual case, the SSO value would be retrieved from the plant historian, allowing for assessment on the plant performance when compared to target and design conditions.

b. Ash Absorption

To calculate the volume of ash water production, the quantity of fly and bottom ash are required. This is established by knowing the ratio of fly to bottom ash. This value can be found in design documentation, acceptance tests, or experimental tests done previously. It was established from design documentation, that the percentage of fly and bottom ash were 25% and 75% respectively for the selected power plant. The coal quality analysed at power plants, containing the as received CV and ash content, is used in equation (4) to obtain the average equivalent coal mass flow for the time period considered.

The coal burn rate (tons/GWh) is calculated using equation (31).

$$\dot{Q}_{coal} = \frac{\dot{m}_{coal} \cdot t}{E_{sso}} \tag{31}$$

The mass of ash (tons) is calculated by using the ash content from the ultimate coal analysis.

$$m_{ash} = E_{sso} \cdot \dot{Q}_{coal} \cdot X_{ash} \tag{32}$$

The volume of ash (Ml) can then be estimated using the ash density in equation (33).

$$v_{ash} = \frac{\dot{m}_{ash}}{\rho_{ash}} \tag{33}$$

The mass of fly and bottom ash can be calculated by using the mass fraction of the ash types. This is defined such that one can either output the mass of coarse or fine ash depending on the mass fraction input into equation (34).

$$m_{ash,\,i} = m_{ash} \cdot X_{ash,\,i} \tag{34}$$

The water loss due to ash absorption is estimated by applying equation (35) with an AIH value of 60% as explained in Section 2.9.1.

$$v_{ash.w} = \frac{m_{ash} \cdot AIH}{\rho_w} \tag{35}$$

c. Rainfall Collection

The first set of equations for climatic impact is based on the rainfall collected. The rainfall is calculated using equation (28) with the raw water dam surface area, average rain intensity for the window period selected, and a run-off coefficient of one. The run-off coefficient is one when all rainwater is collected in the dam (zero run-off). All water storage dams without slopes have a run-off value of one as there is no run-off water, and are therefore omitted from the calculation. Hence, there are two types of rainfall equations, one to calculate the run-off rainwater from slopes, and the other to calculate the rain collected within open dams. Due to the volume flowrate of water required for the window period specified, equation (28) has been amended to include the window period and is given by equation (36) .

$$v_r = f_r \cdot i \cdot A \cdot t \tag{36}$$

The rainfall collection of open dams is calculated using equation (37) .

$$v_{r,pools} = i \cdot A \cdot t \tag{37}$$

These two equations were then applied to all ash and water dams, as well as the station drains to establish the total rainwater collected. The run-off factor used for station drain calculation is one, as all rainwater is collected in trenches that flow to the ash dams. The station drain is treated as an open dam.

d. Evaporation losses

The dam evaporation calculation was conducted similarly to the rainfall collection calculation. However, instead of inputting rain intensity; the evaporation value was used in equation (37). There are two evaporation rates used depending on whether the calculation is for evaporation of a water pool or from an ash dump. Eskom calculates the ash phase evaporation in ash ponds as 80 % of the climatic evaporation rates according to experimental tests conducted on the ashing system. All other water ponds use the 100% evaporation intensity, e_i . The pan factor for the region has to be incorporated in the final evaporation calculation as a correction factor [55]. By applying equation (38) to the water and ash dams, the total evaporation due to weather conditions can be established.

$$v_{E,i} = e_i \cdot A \cdot t \cdot f_{pan} \tag{38}$$

Where:

$v_{E,i}$ = volume of water lost through evaporation for ash dumps or pools (m^3)

e_i = evaporation intensity (m/s)

f_{pan} = pan factor

The rainfall and evaporation values are retrieved from reliable weather sources, while the dam areas can usually be found in design/environmental documents [95]. The total evaporation calculated is corrected using the pan factor. The Excel model uses a value of 0.85 for the pan factor based on the regional characteristics of the power plants [57]. Pan factor values are available in environmental reports or reports from the Department of Water and Sanitation [55].

The biggest form of evaporation loss from the power plant is due to cooling tower evaporation. For the selected power plant, the Excel model uses the design value of 1.563 Ml/GWh in equation (14) for the evaporation loss, and a value of 0.024 Ml/GWh in equation (16) as the windage loss . The windage loss value in the Excel model correlates well to the values outlined in Section 2.8.2. The Excel model makes use of the evaporation loss, windage loss, and the evaporation adjustment factor given by equation (15), for the total volume loss of water from the cooling tower as shown in equation (39).

$$v_{E.CT} = v_E + v_D + v_{cf} \tag{39}$$

Evaporation of water also occurs at the bottom of the boiler, known as bottom ash quenching. This loss is established by using a quenching factor, f_q, of 0.34 from the Excel model, together with the quantity of bottom ash exiting the bottom of the boiler established in equation (34). The quenching factor was calculated based on the assumed ash and water temperatures during ashing and calculated using equation (26).

The evaporation loss due to ash quenching is calculated using equation (40).

$$v_q = \frac{m_{ash,coarse} \cdot f_q}{\rho_w} \tag{40}$$

A small portion of water is also lost through Demin evaporation. Eskom uses a factor, f_{dem}, of 50% of the Demin water supplied to the power plant that will be lost through evaporation. This could either be due to boiler blowdowns, soot blowing or steam leaks. Thus, using the design Demin consumption, I_{dem}, of 0.05 Ml/GWh for the power plant, the volume of Demin lost through evaporation can be established.

$$v_{E.dem} = E_{sso} \cdot I_{dem} \cdot f_{dem} \tag{41}$$

This approach adopted by Eskom is heavily dependent on using design data for the Demin consumption and losses. Improvements on this calculation can be made with more accurate measured data, where available. The percentage loss of potable water as evaporation was not accounted for in the Excel model for setting targets.

e. Ash dam seepage

Ash dam seepage is usually measured at the power plant only during statutory inspections of the ash dams. This value can be neglected, as it is often a small contribution to the total losses. However, if seepage values are recorded during environmental surveys, this should be used as an additional water loss.

f. Raw water consumption

The approach taken in the Excel model was to calculate the total raw water consumption required based on the summation of all the losses mentioned in section (a) to (e) and subtracting rainfall. This is illustrated in equation (42) for the final target water performance value for the power plant.

$$v_{raw} = v_{E.CT} + v_{E.ash} + v_{E.pools} + v_{seepage} + v_{E.dem} + v_{ash.w} + v_q - \left(v_r + v_{r.pools}\right) \tag{42}$$

2.11.2 Water balance model

The Eskom water balance model was developed as a separate Excel tool, independent of the water target tool. The results of the water balance were used to compare to the target values, as well as for performance reporting. The power plant schematic, as indicated in Figure 26, was used to perform the water balance calculations. The approach taken in the Excel water balance model was to work forwards from the raw water supply (Point 1) by defining the raw water inflow as the initial input.

The Eskom water balance model was categorised into specific sub-sections labelled on Figure 26 from Point 1 to Pont 7.

- Point 1: Raw water reservoir
- Point 2: Demin plant
- Point 3: Potable water
- Point 4: Cooling water
- Point 5: Sewage works
- Point 6: Power station drainage
- Point 7: Ash system

The mass balance principle was then applied systematically through each sub-system to solve for the unknown water stream. Figure 13 is a generic layout used for the potable and Demin plant water balance. Eskom made use of a combination of design data, experimental results, and assumptions to develop the potable and Demin systems. The main design assumptions were that 90% of the raw water enters the CW system, and the remainder goes to the pre-treatment plant for potable and Demin production. The flows then split at the pre-treatment plant to potable and Demin by using the design ratio of Demin to potable of 1: 2. As the Demin plant design performance is known, the potable water system flows can thus be calculated.

The design performance of the power plant and CW system were used to calculate the cooling water blowdown flowrates and evaporation losses. The water balance over the CW system was used to then solve for CW overflows to the drainage system.

The effluent and waste disposal from the CW system, potable, and Demin processes was then fed into the sewage plant, drainage system, and ash dam systems completing the system development.

Throughout the model, rainfall and evaporation is accounted for by using the averaged climate conditions for the past ten years, and the station surface areas as discussed in the target tool. The model output was displayed on schematics on Excel indicating the inflows and outflows expected per system based on design conditions. This is valuable when compared to actual flow meter data to indicate plant deviations and abnormalities in processes. Power plants were able to account for water losses and rectify wastages where possible. However, this is only done as once-off simulations when required in Excel.

2.12 EtaPRO monitoring tool

EtaPRO is a software tool developed and supported by General Physics (GP) Strategies Corporation [96]. EtaPRO is a performance, reliability, and optimisation tool for plant efficiency. EtaPRO uses real time performance and condition monitoring, combined with thermal performance, anomaly detection, and machinery dynamics to maintain equipment health, as indicated in Figure 27: EtaPRO system [67]Figure 27.

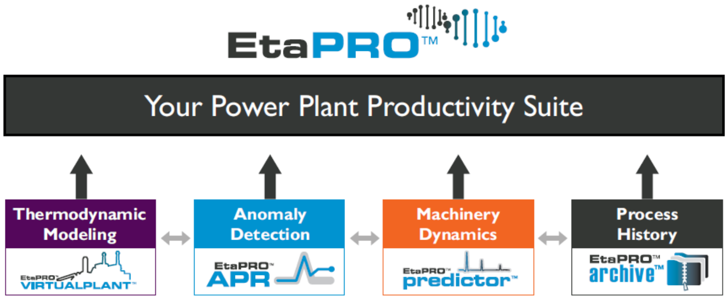


Figure 27: EtaPRO system [67]

EtaPRO uses high-speed data historian, a live logbook, reporting, and alert engines for improving plant availability, capacity, and efficiency. EtaPRO is installed on over 450,000 MW of power generation plants in thirty-eight countries of which Eskom makes up approximately 10% of that power generation.

EtaPRO incorporates numerous capabilities such as [67]:

- System and component performance monitoring that provides comparison of actual to design, target, and expected performance.
- System and component condition monitoring to detect sensor and equipment problems related to equipment operation and maintenance.
- Storage of historical data for plant field readings and calculated values.
- Configuration capabilities available to end-users.
- Historical data filtering and trends based on steady-state operation periods at specified loads.

The EtaPRO System package includes server applications as listed below [67]:

- EtaPRO service manager
- Virtual Plant (VP) editor
- Asset editor

- Server tools
- Plant configuration databases
- EPLog database
- EPArchive historian
- Workstation applications (EtaPRO Client, VP Editor, Asset Editor, and client tools)

2.12.1 EtaPRO Client

EtaPRO Client consists of an intuitive Graphical User Interface (GUI) that provides easy access to real time and historical data. It allows for the development of interactive thermodynamic and empirical models, reports, and diagnostics with alerting capabilities.

Some of the functionalities within the system include:

- Excel-based reporting tool (EPReporter)
- Electronic operations log (EPLog) linked to numerical historical data, critical event notification tool using the Diagnostic Builder with flexible data acquisition options
- Thermodynamic modelling framework (VP)
- An empirical modelling framework (EtaPRO APR)
- A high-performance data historian (EPArchive)
- EtaPRO provides a comprehensive performance calculation library, powerful display builder and advanced trend recovery and analysis tools (EPTrendSetter).
- EtaPRO Web Client allowing EtaPRO screens, trend definitions and footprints, distributed EPReports, and EPLog entries to be viewed using a web browser.

The architecture of EtaPRO is designed on C# (C-sharp) programming language using Microsoft .NET framework. It takes advantage of several commercial software tools as building blocks to develop a customised software application with client-specific features, and to provide the configuration databases.

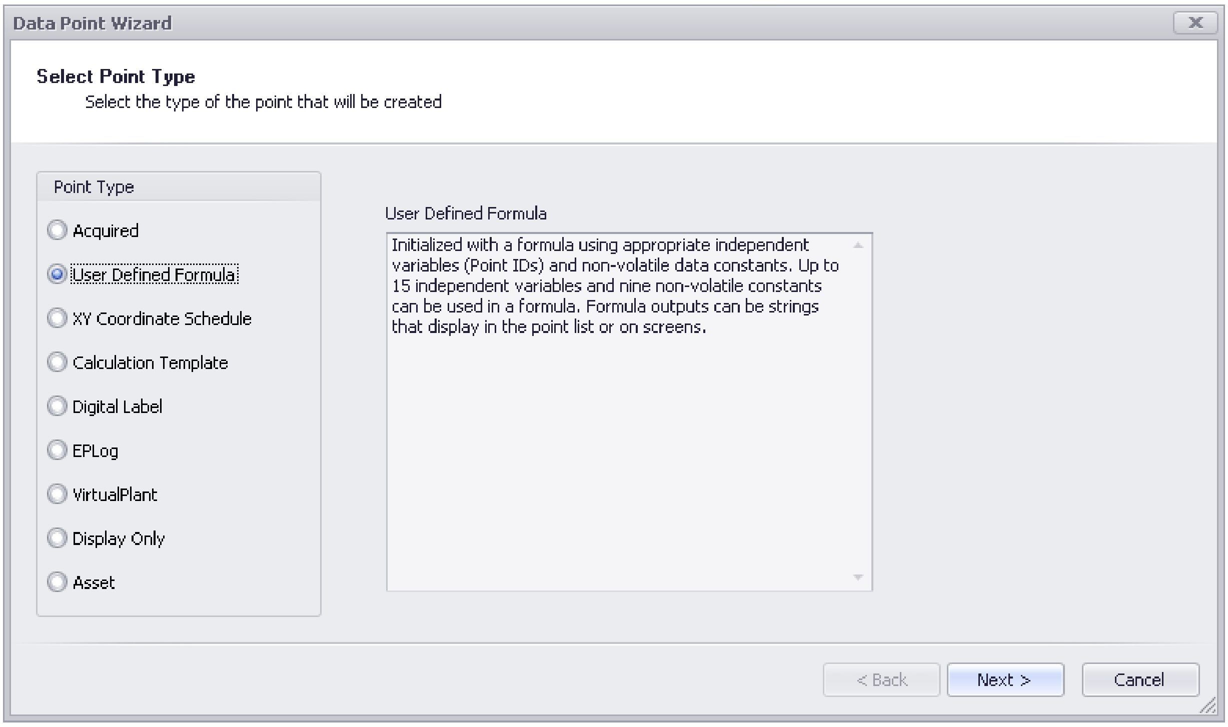
It is important to note that the EtaPRO Calculation Engine is a sequential solver. This implies inputs/variables are defined in a list of EtaPRO database points before use in an equation further down the list.

2.12.2 Data points

Data points in EtaPRO are initialized in a specific sequence called the Initialization Order. When EtaPRO updates, it starts with the data point with an initialization index of one and continues through the entire set of data points defined in the EtaPRO point table, replacing previous values with new values. EtaPRO point updates are typically set to one minute intervals which, can be altered if required. Data points may be acquired from a data source, such as Virtual Plant or EtaPRO APR. Data points can be determined from curve coefficients or schedules, calculated using pre-defined calculation templates or user defined formulae (UDF). A data point may be stand-alone or related to one or more data points. It is useful to know how a particular data point is used. If a data point depends on another data point either as the independent variable in a UDF, schedule, or as an argument to a calculation template; the other data point must be initialized before it. For example, gross load is used extensively throughout EtaPRO as the independent variable for UDF and schedules, and as an argument to many calculations. The data points that are UDF, schedules, and calculations that use gross load are dependent upon the gross load acquired data point. During each update, its value is replaced prior to the new value and is used as the independent variable in subsequent data points.

When a data point is used as an independent variable or calculation argument for a second data point, the dependency of the second point is considered primary. If a third data point has a primary dependency upon this second point, its dependency on the first point is considered secondary. This, of course, can carry onto several levels, where a series of data points are calculated in sequence to arrive at a final value. These dependencies can be easily viewed using the Mapping Tool or by generating a point dependency map report from EtaPRO.

Data points are created via the user interface (Data Point Wizard). There are multiple options for data point creation as illustrated in Figure 28. However, primarily two ways are often used by users to add calculations on EtaPRO, namely **User Defined Formula** and **Calculation Templates.**



User Defined Formula

Initialized with a formula using appropriate independent variables (Point IDs) and non-volatile data constants. Up to 15 independent variables and nine non-volatile constants can be used in a formula. Formula outputs can be strings that display in the point list or on screens.

Figure 28: EtaPRO data point creation screen [67]

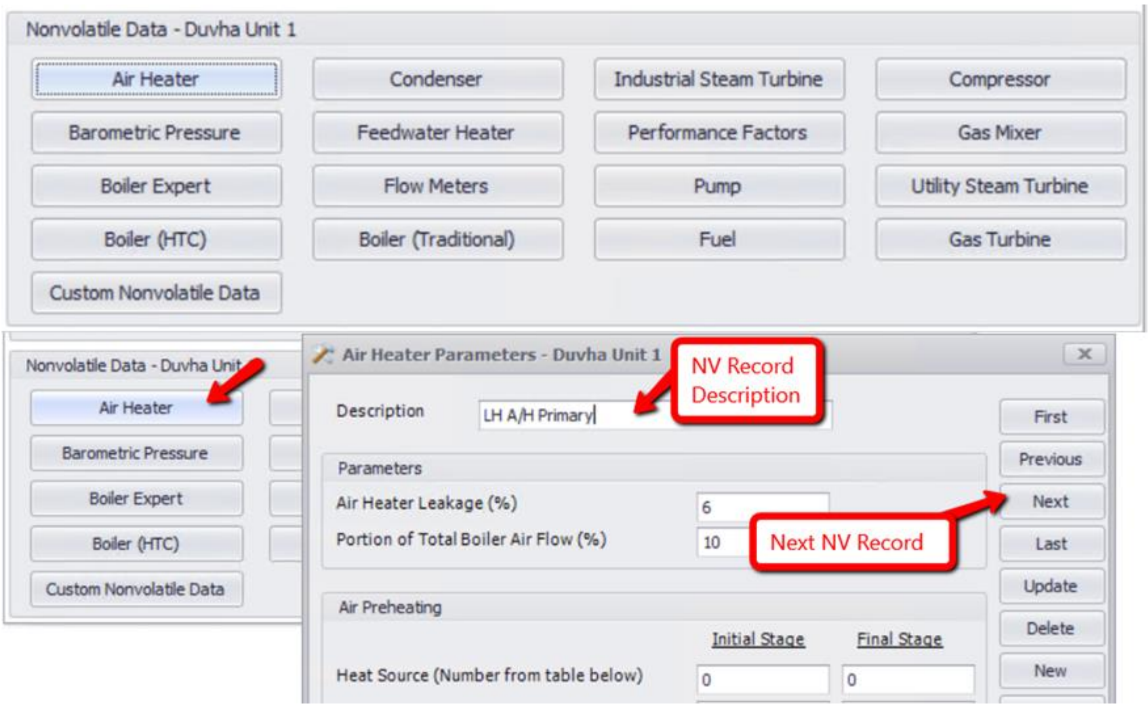
It is important to understand the benefits and shortfalls of the different data point creation methods. Table 7 summarizes the differences between using the method of UDF and calculation templates for creating new data points on EtaPRO.

Table 7: EtaPRO data acquisition comparison for UDF and calculation templates

	User Defined Formula	**Calculation Template**
User freedom	Allows the user to set up any form of calculation using various inputs	Contains a pre-determined calculation where the user can only choose which inputs are used
Typically Use	All purposes, with general customization	To standardize calculations
Editing	User friendly via the EtaPRO Client UI (requires reconfiguration, no system downtime)	Requires reviewing of C# code and the calculation engine needs restarting (requires system downtime)
Security	Medium. User changes are logged and edit permissions are controlled via the User Management interface.	High. Data points cannot be edited form EtaPRO Client, changing C# Plugins requires source code, and changes to permanent data are logged.

2.12.3 Non Volatile Data

A Non Volatile (NV) Record refers to a NV Data set for either a built-in module or a module in Custom NV Data. NV Data, commonly refers to the permanent data for a NV Record in a module. All NV Data can be changed in edit mode. These records allow multiple cases to be defined (different permanent data) for the same system receiving real time data. The user will have the ability to capture permanent design data, read curves, or have drop-down options. A NV Record is a pre-defined data structure developed in C#. It allows users to create multiple instances and enter different values for the different instances. There are NV records for built-in modules such as the Pump, Boiler, Turbine, Condenser, etc. as well as custom NV Data modules as shown in Figure 29.



Description: LH A/H Primary

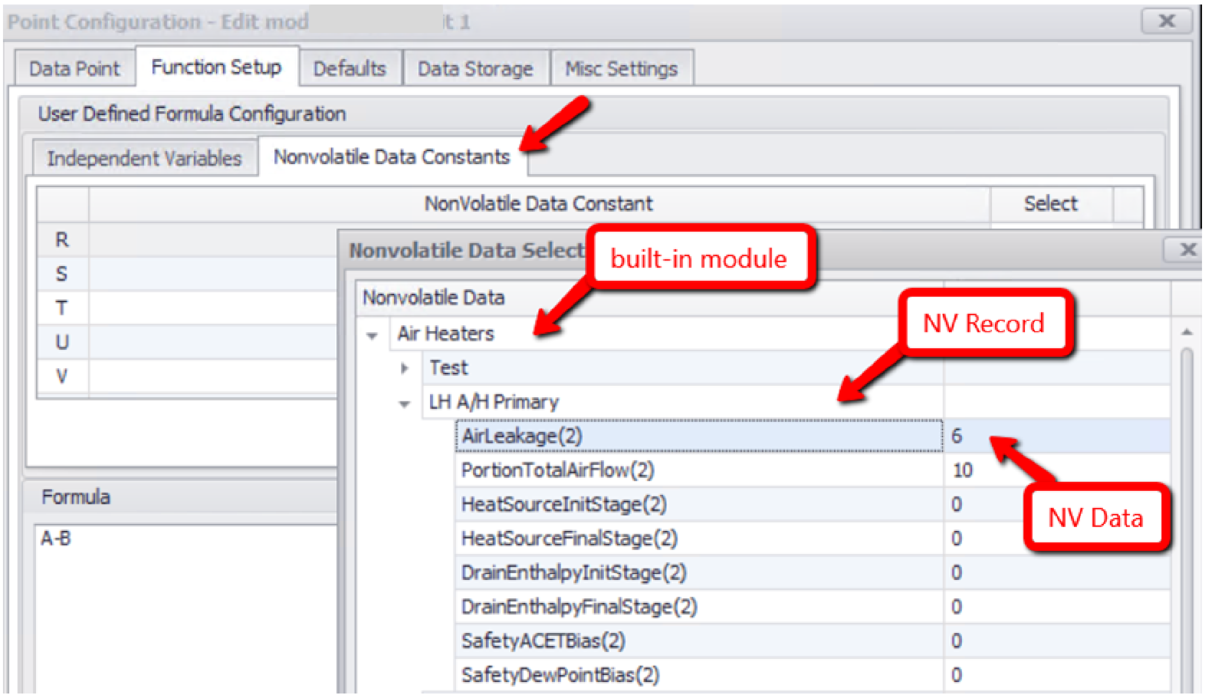
Air Heater Leakage (%): 6

Portion of Total Boiler Air Flow (%): 10

Heat Source (Number from table below): Initial Stage 0, Final Stage 0

Figure 29: NV records for built in modules [67]

UDF calculations make use of NV Data as constants from a built-in module only. This is done by selecting the NV Data from a NV Record for a built-in module as illustrated in Figure 30.

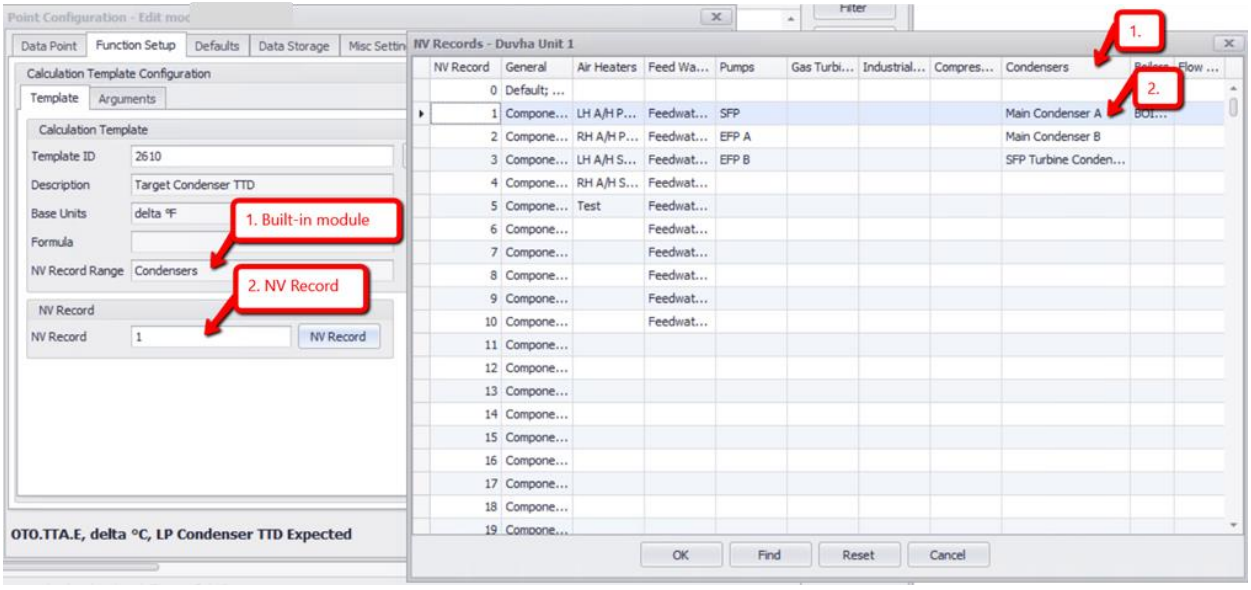


Formula: A-B

Nonvolatile Data	
AirLeakage(2)	6
PortionTotalAirFlow(2)	10
HeatSourceInitStage(2)	0
HeatSourceFinalStage(2)	0
DrainEnthalpyInitStage(2)	0
DrainEnthalpyFinalStage(2)	0
SafetyACETBias(2)	0
SafetyDewPointBias(2)	0

Figure 30: NV Record and NV Data selection for UDF calculations [67]

Built-in Calculation Templates have NV Data associations to built-in modules with NV Records only as indicated in Figure 31.



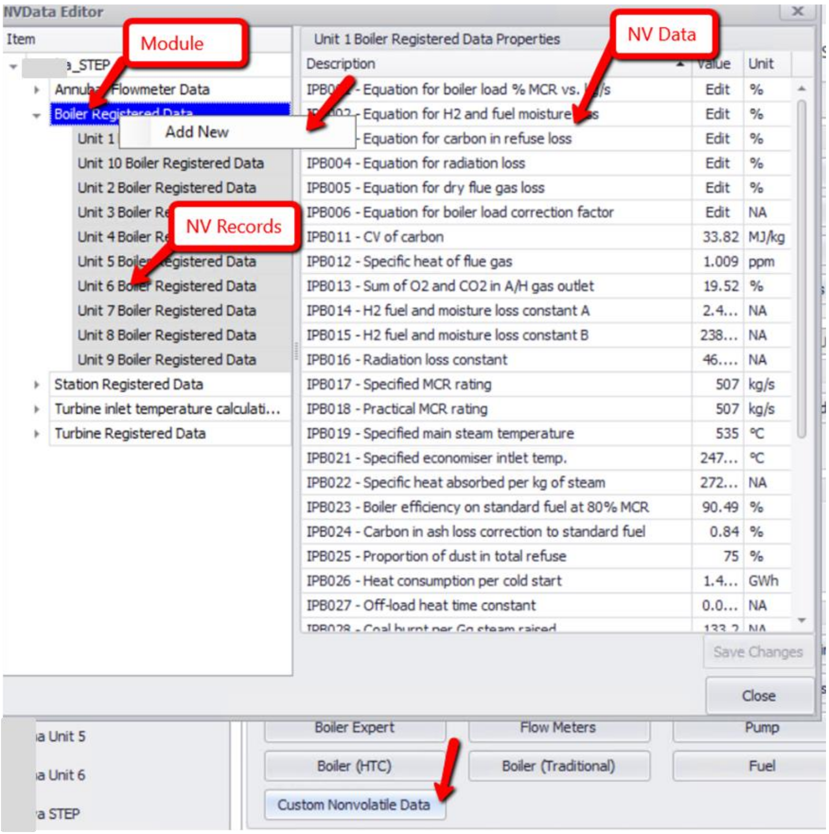
Template ID: 2610
Description: Target Condenser TTD
Base Units: delta °F
Formula:
NV Record Range: Condensers
NV Record: 1

OTO.TTA.E, delta °C, LP Condenser TTD Expected

NV Record	General	Air Heaters	Feed Wa...	Pumps	Gas Turbi...	Industrial...	Compres...	Condensers	Boilers	Flow ...
0	Default; ...									
1	Compone...	LH A/H P...	Feedwat...	SFP				Main Condenser A	BOI...	
2	Compone...	RH A/H P...	Feedwat...	EFP A				Main Condenser B		
3	Compone...	LH A/H S...	Feedwat...	EFP B				SFP Turbine Conden...		
4	Compone...	RH A/H S...	Feedwat...							
5	Compone...	Test	Feedwat...							
6	Compone...		Feedwat...							
7	Compone...		Feedwat...							
8	Compone...		Feedwat...							
9	Compone...		Feedwat...							
10	Compone...		Feedwat...							
11	Compone...									
12	Compone...									
13	Compone...									
14	Compone...									
15	Compone...									
16	Compone...									
17	Compone...									
18	Compone...									
19	Compone...									

Figure 31: NV Record selection for a Calculation Template [67]

Custom NV Data has modules with NV Records associated with Custom Calculation Templates. These NV Records have NV Data sets. New NV Records with NV Data sets can be added to a module as shown in Figure 32.



Item
- [redacted]a_STEP
  - Annub Flowmeter Data
  - Boiler Registered Data
    - Unit 1
    - Unit 10 Boiler Registered Data
    - Unit 2 Boiler Registered Data
    - Unit 3 Boiler Re
    - Unit 4 Boiler Re
    - Unit 5 Boile egistered Data
    - Unit 6 Bo r Registered Data
    - Unit 7 Boiler Registered Data
    - Unit 8 Boiler Registered Data
    - Unit 9 Boiler Registered Data
  - Station Registered Data
  - Turbine inlet temperature calculati…
  - Turbine Registered Data

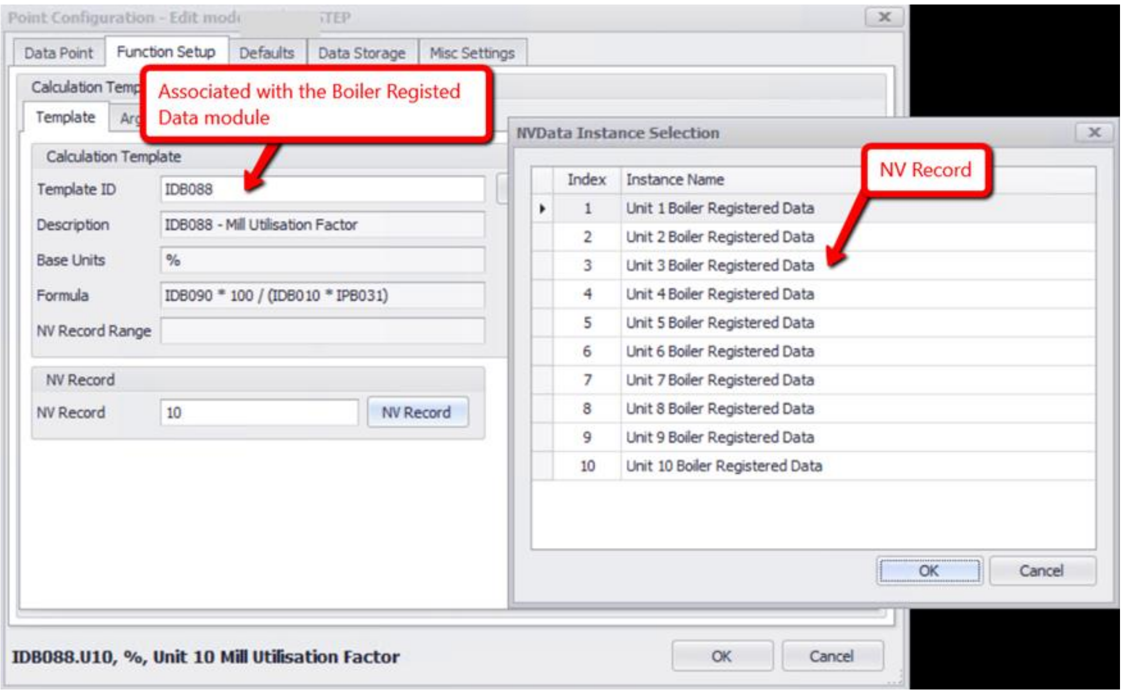
a Unit 5
a Unit 6
a STEP

Unit 1 Boiler Registered Data Properties

Description	Value	Unit
IPB0 - Equation for boiler load % MCR vs. /s	Edit	%
I 02 - Equation for H2 and fuel moisture s	Edit	%
- Equation for carbon in refuse loss	Edit	%
IPB004 - Equation for radiation loss	Edit	%
IPB005 - Equation for dry flue gas loss	Edit	%
IPB006 - Equation for boiler load correction factor	Edit	NA
IPB011 - CV of carbon	33.82	MJ/kg
IPB012 - Specific heat of flue gas	1.009	ppm
IPB013 - Sum of O2 and CO2 in A/H gas outlet	19.52	%
IPB014 - H2 fuel and moisture loss constant A	2.4…	NA
IPB015 - H2 fuel and moisture loss constant B	238…	NA
IPB016 - Radiation loss constant	46.…	NA
IPB017 - Specified MCR rating	507	kg/s
IPB018 - Practical MCR rating	507	kg/s
IPB019 - Specified main steam temperature	535	°C
IPB021 - Specified economiser intlet temp.	247…	°C
IPB022 - Specific heat absorbed per kg of steam	272…	NA
IPB023 - Boiler efficiency on standard fuel at 80% MCR	90.49	%
IPB024 - Carbon in ash loss correction to standard fuel	0.84	%
IPB025 - Proportion of dust in total refuse	75	%
IPB026 - Heat consumption per cold start	1.4…	GWh
IPB027 - Off-load heat time constant	0.0…	NA
IPB028 - Coal burnt per Gg steam raised	133.2	NA

Figure 32: Custom NV Data structure [67]

Figure 33 shows how a NV record is selected when creating an EtaPRO point using a calculation template.



Point Configuration - Edit mod[redacted]TEP

Associated with the Boiler Registed Data module

Calculation Template

Template ID: IDB088
Description: IDB088 - Mill Utilisation Factor
Base Units: %
Formula: IDB090 * 100 / (IDB010 * IPB031)
NV Record Range:

NV Record

NV Record: 10

NVData Instance Selection

NV Record

Index	Instance Name
1	Unit 1 Boiler Registered Data
2	Unit 2 Boiler Registered Data
3	Unit 3 Boiler Registered Data
4	Unit 4 Boiler Registered Data
5	Unit 5 Boiler Registered Data
6	Unit 6 Boiler Registered Data
7	Unit 7 Boiler Registered Data
8	Unit 8 Boiler Registered Data
9	Unit 9 Boiler Registered Data
10	Unit 10 Boiler Registered Data

IDB088.U10, %, Unit 10 Mill Utilisation Factor

Figure 33: NV Record selection for Calculation Templates [67]

2.12.4 EtaPRO data flow

The majority of EtaPRO systems are installed in network environments to allow sharing of performance and condition monitoring information across the enterprise. The EtaPRO server is connected to the plant’s Local Area Network (LAN) or the company’s Wide Area Network (WAN). Any EtaPRO computer with access to the network and user credentials, can access the EtaPRO features. This includes viewing calculated results and retrieving historical data. The physical architecture of the system is represented in Figure 34.

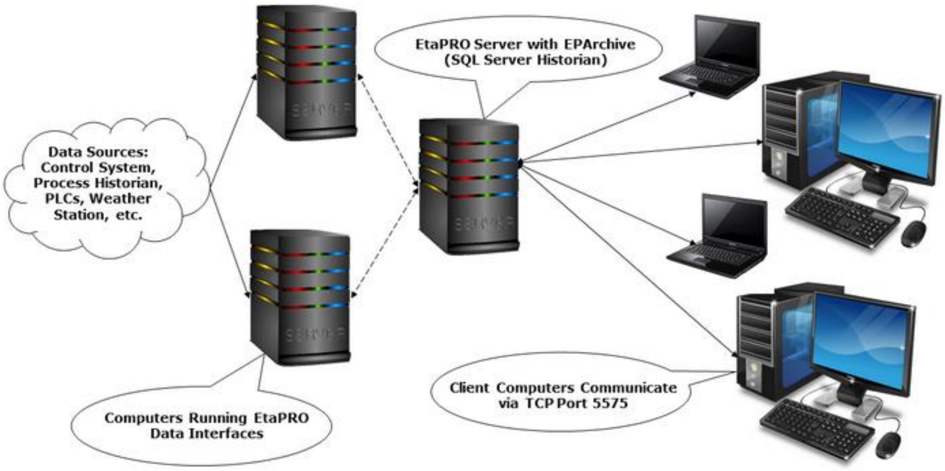
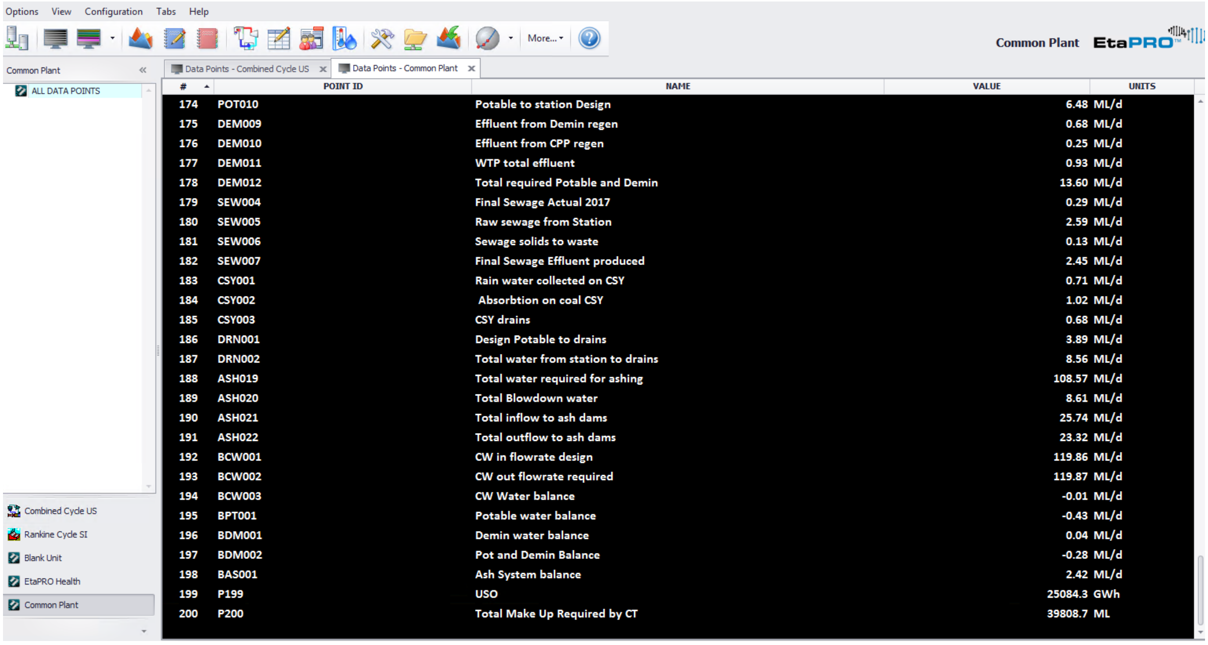


Figure 34: Physical architecture of the EtaPRO network [33]

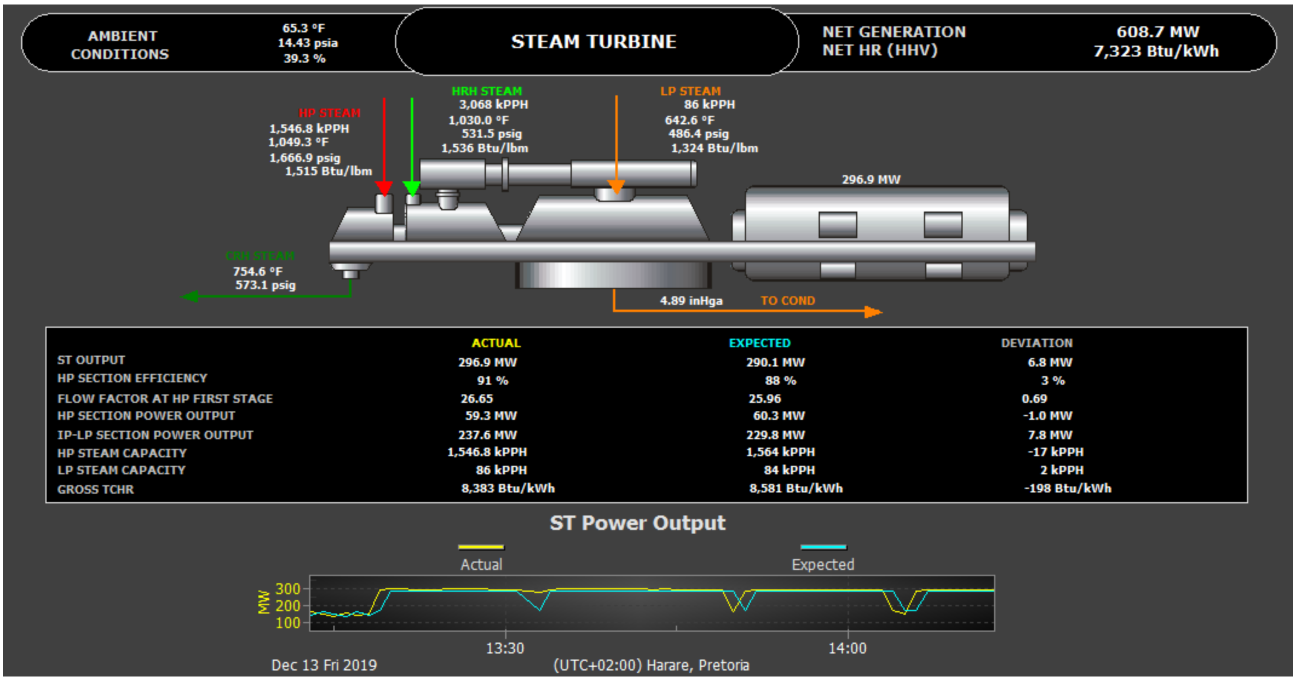
EtaPRO Client user interface is illustrated in Figure 35, showing the list of data points created in sequential order.



#	POINT ID	NAME	VALUE	UNITS
174	POT010	Potable to station Design	6.48	ML/d
175	DEM009	Effluent from Demin regen	0.68	ML/d
176	DEM010	Effluent from CPP regen	0.25	ML/d
177	DEM011	WTP total effluent	0.93	ML/d
178	DEM012	Total required Potable and Demin	13.60	ML/d
179	SEW004	Final Sewage Actual 2017	0.29	ML/d
180	SEW005	Raw sewage from Station	2.59	ML/d
181	SEW006	Sewage solids to waste	0.13	ML/d
182	SEW007	Final Sewage Effluent produced	2.45	ML/d
183	CSY001	Rain water collected on CSY	0.71	ML/d
184	CSY002	Absorbtion on coal CSY	1.02	ML/d
185	CSY003	CSY drains	0.68	ML/d
186	DRN001	Design Potable to drains	3.89	ML/d
187	DRN002	Total water from station to drains	8.56	ML/d
188	ASH019	Total water required for ashing	108.57	ML/d
189	ASH020	Total Blowdown water	8.61	ML/d
190	ASH021	Total inflow to ash dams	25.74	ML/d
191	ASH022	Total outflow to ash dams	23.32	ML/d
192	BCW001	CW in flowrate design	119.86	ML/d
193	BCW002	CW out flowrate required	119.87	ML/d
194	BCW003	CW Water balance	-0.01	ML/d
195	BPT001	Potable water balance	-0.43	ML/d
196	BDM001	Demin water balance	0.04	ML/d
197	BDM002	Pot and Demin Balance	-0.28	ML/d
198	BAS001	Ash System balance	2.42	ML/d
199	P199	USO	25084.3	GWh
200	P200	Total Make Up Required by CT	39808.7	ML

Figure 35: EtaPRO Client user interface [67]

Figure 36 illustrates the capabilities of the EtaPRO user interface to create dashboards with plant configuration, while also indicating data point trends over time. This can be customised to any plant configuration, and output data according to user requirements.



AMBIENT CONDITIONS 65.3 °F 14.43 psia 39.3 %

STEAM TURBINE

NET GENERATION 608.7 MW
NET HR (HHV) 7,323 Btu/kWh

	ACTUAL	EXPECTED	DEVIATION
ST OUTPUT	296.9 MW	290.1 MW	6.8 MW
HP SECTION EFFICIENCY	91 %	88 %	3 %
FLOW FACTOR AT HP FIRST STAGE	26.65	25.96	0.69
HP SECTION POWER OUTPUT	59.3 MW	60.3 MW	-1.0 MW
IP-LP SECTION POWER OUTPUT	237.6 MW	229.8 MW	7.8 MW
HP STEAM CAPACITY	1,546.8 kPPH	1,564 kPPH	-17 kPPH
LP STEAM CAPACITY	86 kPPH	84 kPPH	2 kPPH
GROSS TCHR	8,383 Btu/kWh	8,581 Btu/kWh	-198 Btu/kWh

Figure 36: EtaPRO dashboard and trending capabilities [67]

3. Methodology

Eskom currently has two separate water management tools that are used for setting the water consumption targets for each power plant, as well as for the site water management requirements. These models were developed based on the information available at the time and to meet the Water User Licence (WUL) requirements. Due to changes in data availability and plant requirements, a need arose for the review of existing water tools, and the development of a new water balance framework. This chapter will outline the methodology followed in developing a water balance that can be built in EtaPRO using a combination of existing Eskom models and the literature captured in Chapter 2.

3.1 Design water balance framework development

The fundamental principle behind the development of a water balance framework is defining the system of mass balances. This is because the flow of water streams can be diagrammatically represented as a flow network, with various inlets and outlets, and internal branches where the conservation of mass must be applied. Due to the traditional platform used for generating a water balance, i.e. Excel, the calculations are performed in a sequential manner. This means that the various branches are solved sequentially, instead of simultaneously as is found in other flow network tools. This sequential solving limitation also exists on the new platform, EtaPRO, therefore the model is developed to enable sequential solving.

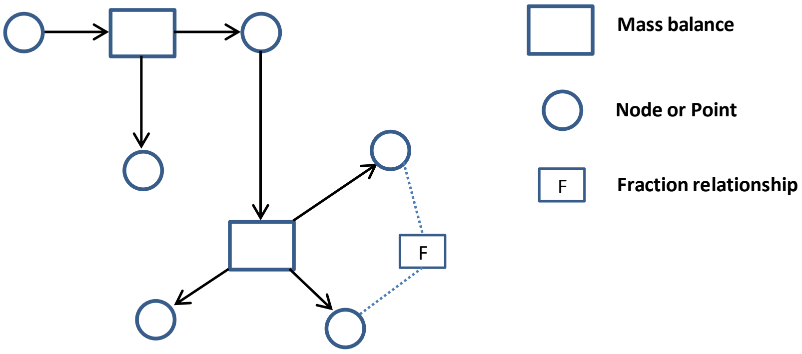


Figure 37: Generic mass balance network development

Figure 37 shows a generic flow network made up of nodes or points and mass balances. A point can be considered as a measurement location in a pipe. Rainfall collection can be seen as if all the rain is first collected and then ducted into the receiving dam. The streams merge or split into various paths at the mass balance nodes. There is a pre-determined flow direction indicated by the arrows. In most cases, the flow is always positive due to the nature of the system described. Some nodes can also be defined as a fraction of the flow in another node.

The aim is to set up a sequence of calculations such that a value can be obtained for all the identified nodes. One would start at the nodes with known or calculable values, and work systematically through the network defining fractions where possible, and solving for mass balances. Mass balances can only be solved if all but one flow is known.

To retain positive value for the flows, generic inflow and outflow mass balance equations are defined as equation (43) and equation (44). The MB_IN function receives all known inputs and outputs, and calculates a single unknown inflow. The MB_OUT function calculates a single unknown outflow.

$$MB\_IN(IN, OUT) = \sum OUT - \sum IN \tag{43}$$

$$MB\_OUT(IN, OUT) = \sum IN - \sum OUT \tag{44}$$

3.2 Water balance model developmental steps

This section will describe the method of how to establish a water balance using the Demin and potable water systems as an example. The design base water balance will be demonstrated, which would eventually serve as the target setting model.

3.2.1 Demin plant

Step 1: Identify plant configuration with all input and output streams

It is imperative that the plant configuration is captured as accurately as possible, with all inputs and output streams clearly indicated. This forms the basis of setting up the water balance. Figure 38 illustrates the schematic for the Demin plant. The blocks typically depict equipment in the system, which performs some process operation, resulting in splitting / combining of streams. These blocks are therefore the mass balance blocks, where each line represents a node.

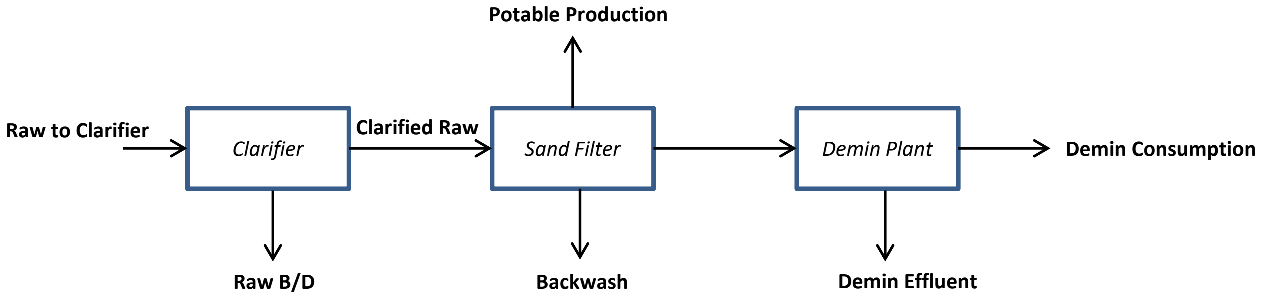


Figure 38: Pre-treatment schematic (step1)

Step 2: Develop a water flow tree with all streams, nodes and mass balances

The next step as shown in Figure 38 entails transforming the plant process structure into a more defined water flow network indicating the water flow direction, stream nodes and mass balance. This provides the basis for the model development structure.

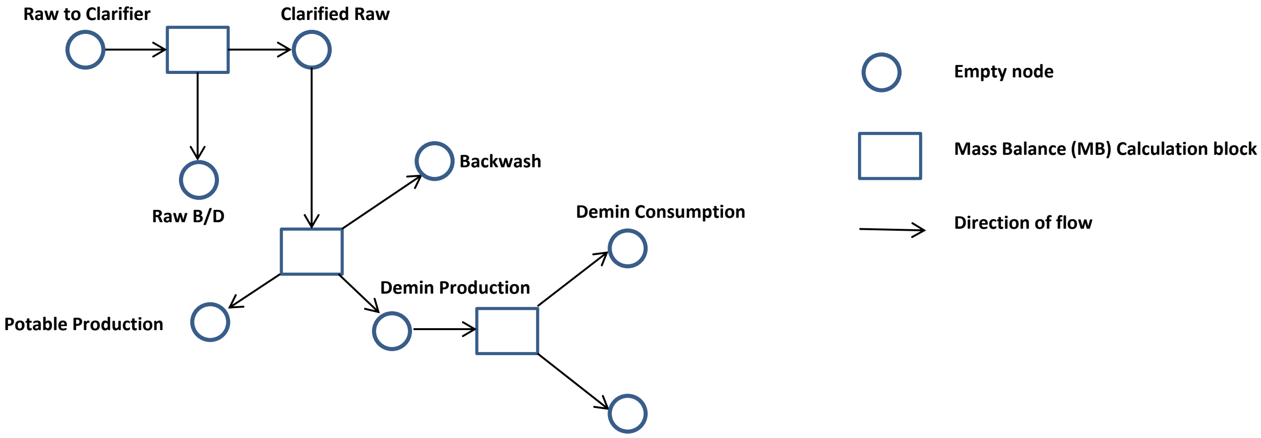


Figure 39: Water balance tree structure (step 2)

Step 3: Indicate known input on empty nodes with identification tags

Once the model structure is defined, the empty nodes can be populated with known data, which either can be design data for the design case, or metered values for the actual consumption model. Figure 40 illustrates this process for the Demin consumption. The Demin plant design is based on the Demin water demand by the power plant. Due to plant deterioration, this can increase over time. The design case model is developed to capture what the design performance should be for comparison later on. A naming convention was developed for data point identification (ID), which will be used later on in the EtaPRO model development.

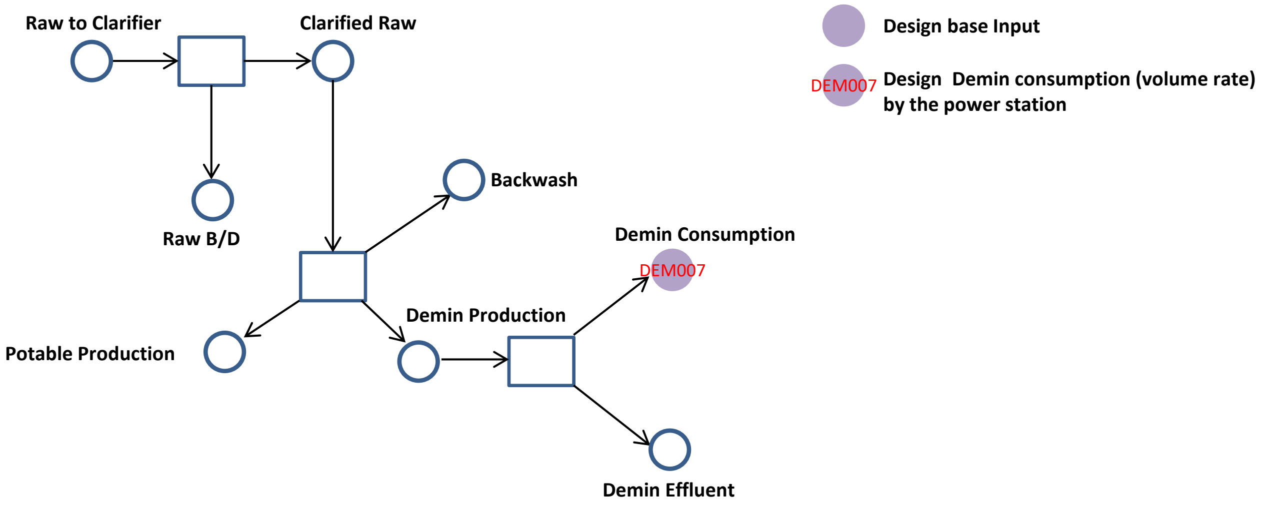


Figure 40: Design data identification (step 3)

Equation (45) is used to establish the design volumetric flowrate, $\dot{V}_{dem}$, indicated by node DEM007. The design Demin consumption, I_{dem} = 0.05 Ml/GWh for the selected power plant, is used with the net electrical output conditions [97].

$$\dot{V}_{dem} = I_{dem} \cdot \dot{W}_{sso} \tag{45}$$

The Demin design operation and vessel capacities are available in the Demin plant OEM manuals. Performance tests usually conducted by specialists at a predetermined frequency can be used as updated values if there are deviations from design conditions.

Step 4: Indicate calculation/assumptions on empty nodes with identification tags

The second type of node input is defined as either calculations or assumptions described by the process itself. In the pre-treatment plant, these were identified as the raw clarifier blowdown and the Demin plant effluent production. The development of calculation templates will be discussed in Section 3.6. Calculation templates identified should also be indicated by the template name. Calculation templates WMSC14 (Raw Clarifier Blowdown) and WMSC15 (WTP Effluent) are the two templates identified in Figure 41.

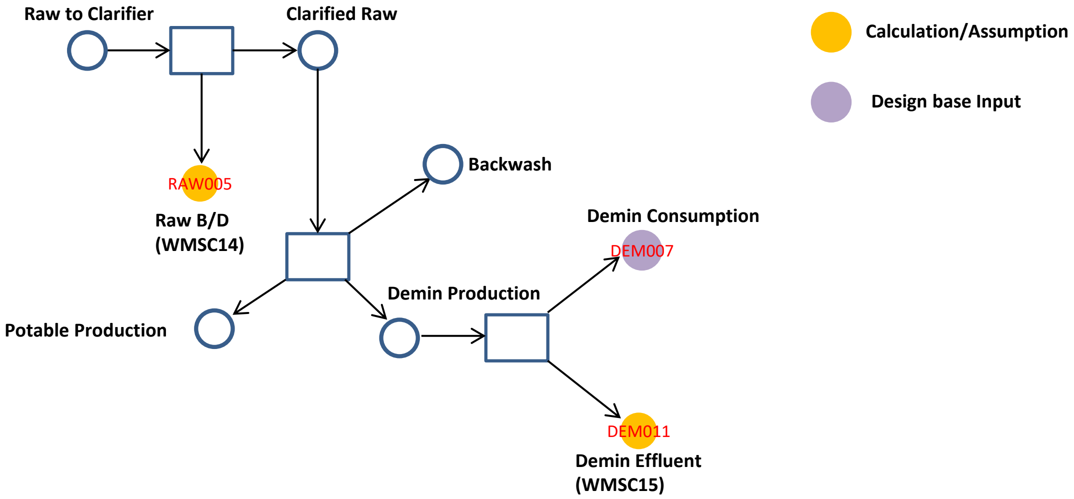


Figure 41: Calculation template and assumption identification (step 4)

The Demin plant has a predetermined throughput and regeneration cycle, which can be obtained from the design documentation. The regeneration process generates effluent from the Demin plant and CPP plant. For simplification, both the Demin and CPP plant effluents will be combined as one node. The quantity of effluent produced can be estimated based on the number of regenerations conducted in a day and the design usage of water per regeneration. By using the design values indicated, the effluent flow out of the system can be estimated. Equation (46) and (47) are used to establish the effluent flows from the Demin and CPP plant.

$$\dot{v}_{eff.dem} = \frac{\dot{v}_{dem}}{v_{dem.cap}} \cdot v_{dem.regen} \tag{46}$$

$$\dot{v}_{eff.cpp} = n_{regen} \cdot v_{cpp.regen} \tag{47}$$

Where:

$v_{dem.cap}$ = design Demin train capacity according to OEM manual (m^3)

$v_{dem.regen}$ = design volume of regeneration water used per Demin regen (m^3)

$v_{cpp.regen}$ = design volume of regeneration water used per CPP regen (m^3)

n_{regen} = number of CPP regenerations per day based on normal operation (s^{-1})

Combining the individual effluent streams as indicated in equation (48), provides the total effluent production at node DEM011.

$$\dot{v}_{t.eff} = \dot{v}_{eff.dem} + \dot{v}_{eff.cpp} \tag{48}$$

Calculation template WMSC15 (details in Appendix B) combines equation (46), equation (47) and equation (48).

The clarifier blowdown (node RAW005) is a function of the total raw water entering the clarifier. This is determined at the design stage of the clarifier and is covered in Section 2.7.1. This value can be confirmed via experimental analysis of the blowdown water. The developer of the Eskom models conducted experimental tests at a power plant in order to determine the percentage of solids in the raw water clarifier. These tests can be conducted based on plant and raw water quality changes and adjusted accordingly. The blowdown factor, used to calculate the volume of blowdown water, is defined in equation (49).

$$f_2 = \frac{T}{f_s \cdot \rho_w} \cdot \frac{1}{3} \frac{mg}{l} \tag{49}$$

Where:

f_s = percentage of solids in raw water to clarifier (%)

T = turbidity of raw water to clarifier (NTU)

Since the raw water entering the clarifier is the final result required from the water balance, it is more logical to define the blowdown flow relative to the outlet of the clarifier. This information will become available once the lower levels of the tree have been calculated. Node RAW005, is then calculated by equation (50) that has been captured in calculation template WMSC14.

$$\begin{aligned} \dot{V}_{BD.raw} &= f_2 \cdot \dot{V}_{raw} \\ \dot{V}_{BD.raw} &= \left(\frac{f_2}{1 - f_2} \right) \cdot \dot{V}_{cl.out} \end{aligned} \tag{50}$$

Step 5: Identify which points can be the result of a mass balance and define factor relationships

Points that are a result of a mass balance calculation are identified, starting at the nodes with known or calculated values, and working upwards. The mass balance blocks should be identified as either MB_IN or MB_OUT calculation.

If more than one unknown point around a water balance exists, the unknown point should be defined in terms of a fraction of a known point. In this system there are two fractions defined for the potable production and the backwash water flow. A design ratio of Demin to potable water flow of 1:2 was defined as the first factor [61]. The backwash flow was previously defined as a function of the raw clarifier outflow. Since this is unknown, a new factor had to be defined in terms of the potable and Demin flows. This led to a split of the sand filter mass balance to enable the definition of the backwash flow.

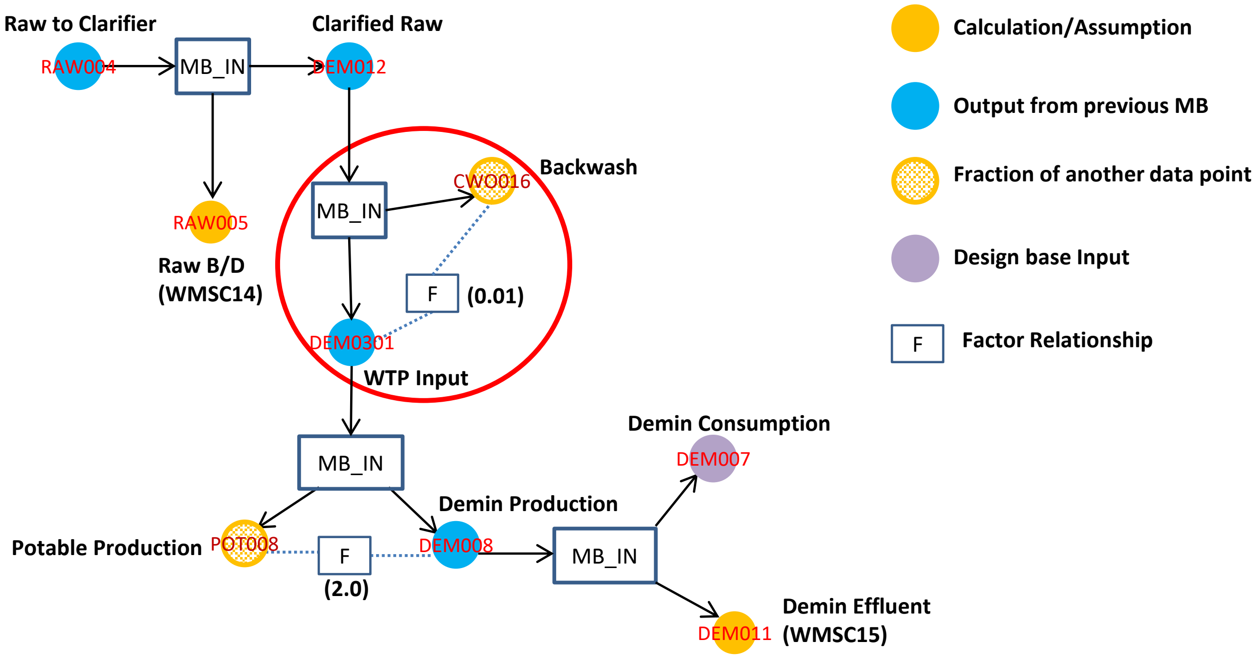


Figure 42: Mass balance outputs and factor description (step 5)

The inflow to the Demin plant, $\dot{v}_{t.dem}$ (node DEM008), can be calculated using a mass balance calculation since all other points are known. The MB_IN calculation is applied in equation (51), with two outflows and no other inflows.

$$\dot{v}_{t.dem} = MB\_IN\left(\begin{bmatrix}0\\0\end{bmatrix}, \begin{bmatrix}\dot{v}_{dem.st}\\ \dot{v}_{t.eff}\end{bmatrix}\right) \tag{51}$$

The potable water production, $\dot{v}_p$ (node POT008), can be estimated by using the potable to Demin factor relationship.

$$\begin{gathered}\dot{v}_p = \dot{v}_{t.dem}\cdot f_1\\ f_1 = 2\end{gathered} \tag{52}$$

The mass balance equation is applied again to establish the input flow to the WTP (node DEM301), which is again an inflow result as depicted by equation (53).

$$\dot{v}_{pot\_dem} = MB\_IN\left(\begin{bmatrix}0\\0\end{bmatrix},\begin{bmatrix}\dot{v}_{t.p}\\\dot{v}_{t.dem}\end{bmatrix}\right) \tag{53}$$

The WTP design manuals indicate that approximately 1% of the output flow from the sand filters will be used for back washing [65]. The backwash flow (node CWO16) is thus a fraction calculation as shown in equation (54).

$$\begin{aligned}\dot{v}_{bw} &= \dot{v}_{pot\_dem}\cdot f_{bw}\\ f_{bw} &= 0.01\end{aligned} \tag{54}$$

With node DEM301 and node CWO016 now known, the inflow to the sand filter (node DEM012) can be calculated from the mass balance equation (55).

$$\dot{v}_{cl.out} = MB\_IN\left(\begin{bmatrix}0\\0\end{bmatrix},\begin{bmatrix}\dot{v}_{bw}\\\dot{v}_{pot\_dem}\end{bmatrix}\right) \tag{55}$$

The raw water input into the potable and Demin clarifier (node RAW004) can be established by performing a mass balance around the clarifier.

$$\dot{v}_{cl.in} = MB\_IN\left(\begin{bmatrix}0\\0\end{bmatrix},\begin{bmatrix}\dot{v}_{BD.raw}\\\dot{v}_{cl.out}\end{bmatrix}\right) \tag{56}$$

Step 6: Identify calculation sequence

The last step requires the identification of the calculation sequence, which can be seen as point 1 to point 9 on Figure 43. The sequential order can vary depending on the data points available or known. Figure 43 shows the complete water balance model with all relevant information required for implementation in EtaPRO.

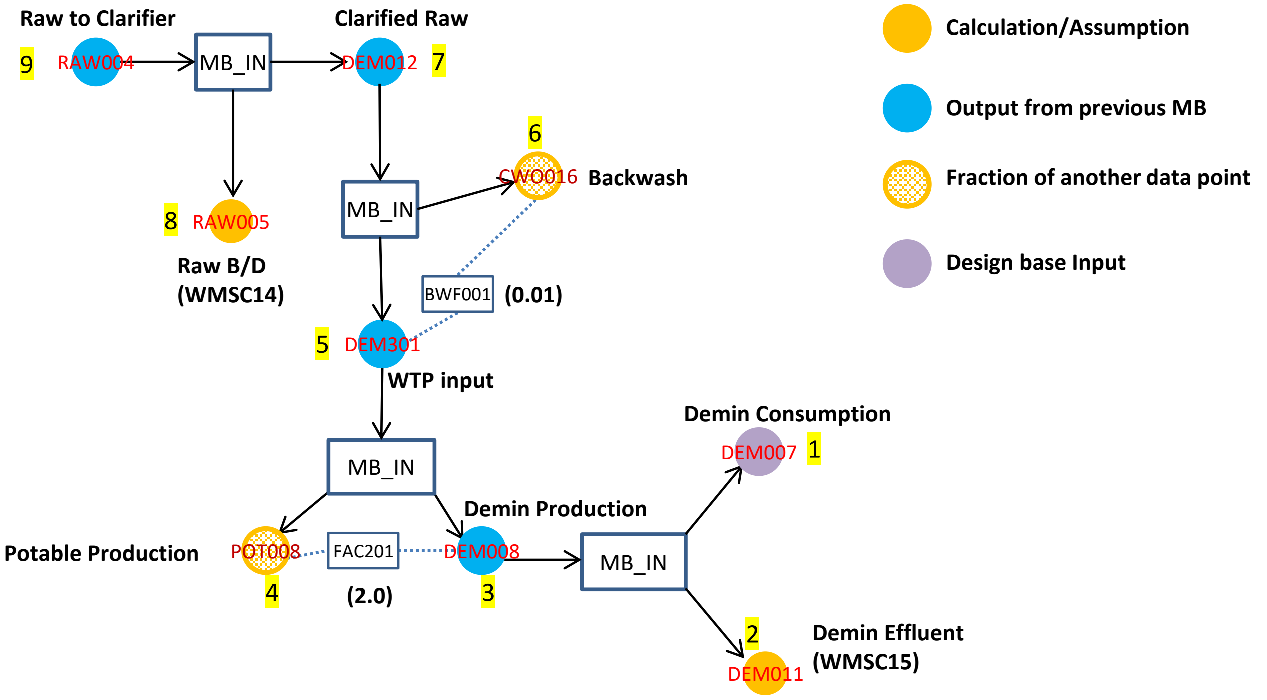


Figure 43: Initialisation order (step 6)

3.2.2 Potable water plant

The potable system balance was developed based on the potable distribution as per Figure 44.

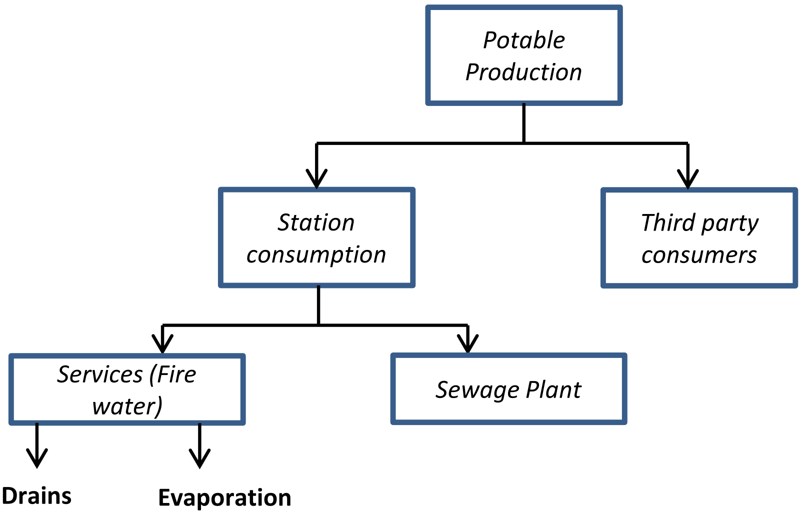


Figure 44: Potable system plant configuration (step 1)

Using the method outlined in Section 3.2, the potable system framework can be developed for the design case as shown in Figure 45.

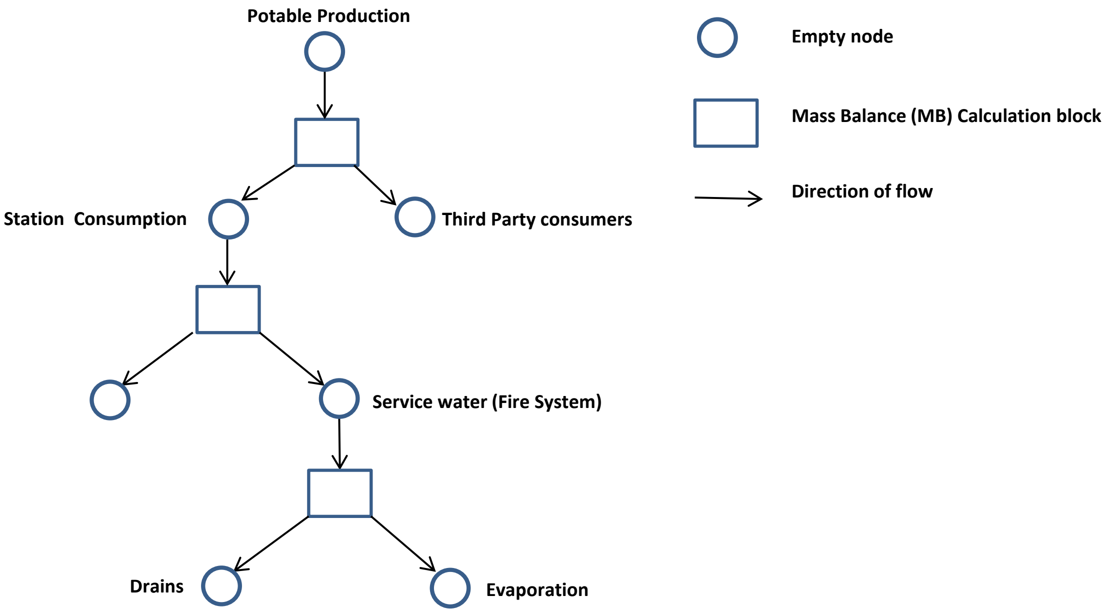


Figure 45: Water flow tree with stream data points (step 2)

The potable production in Figure 46 of the framework is shown as an input, node POT008, as it was calculated at Point 4 from the Demin mass balance in Figure 43 . The third party consumers consist of potable supply to external parties, such as mines. This value is input as a design input as it is determined according to contractual agreements between Eskom and the mine.

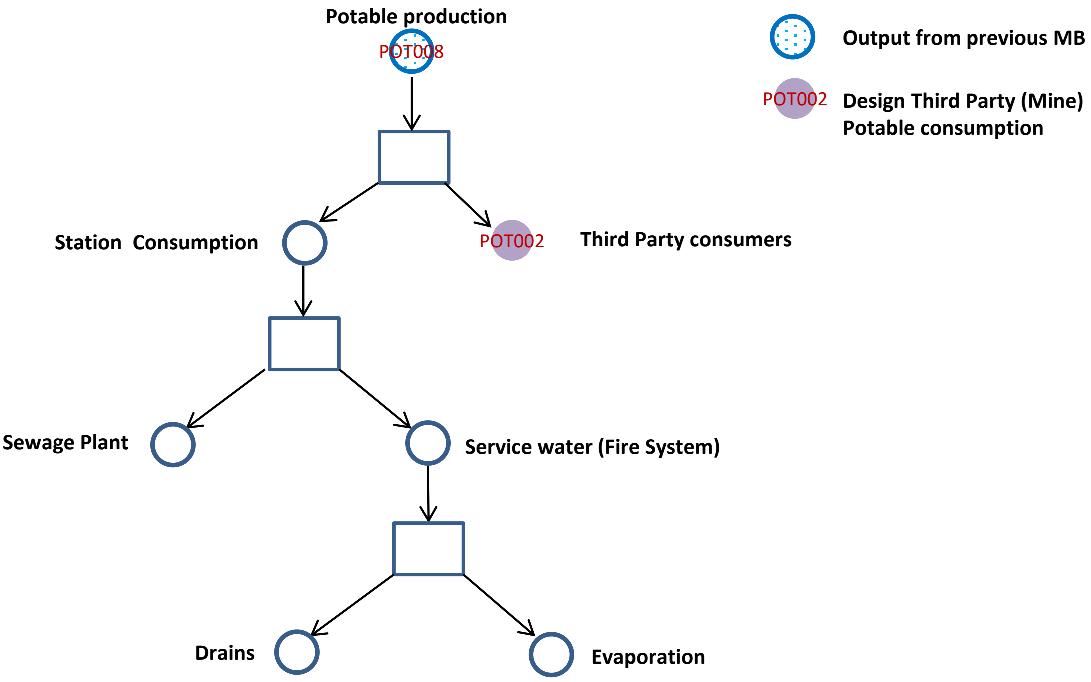


Figure 46: Data point inputs known (step 3)

The Excel model uses assumptions for the potable water distribution to the sewage plant and for cleaning purposes, as there were no measurements available at the time of development. Hence, assumptions also have to be made on the amount of water used for cleaning and domestic use. The Excel model assumes that 40% of potable water is used for domestic use (raw sewage). Historic data averaged over the past 5 years from the sewage plant logbooks were used to work out the amount of raw sewage entering the sewage plant. This value amounted to 10% of the potable water sent to the power plant for domestic use and ends up as raw sewage. Based on this data, the factor SEW002 was changed from 0.4 to 0.1.

There is insufficient knowledge on how much potable water is used for cleaning purposes only, and what portion of this water is recovered back into the system via the drains, as well as what portion is lost due to evaporation. An initial assumption of 4% of the firewater lost to drains was made in order to proceed with the model. This assumption was based on the fact that majority of the potable water is lost during floor washing and cooling of equipment in the form of evaporation. It should be noted that all design factors and assumptions are captured as user inputs into the model and can be adjusted as more accurate data becomes available. Figure 47 illustrates the factor relationships for the potable system.

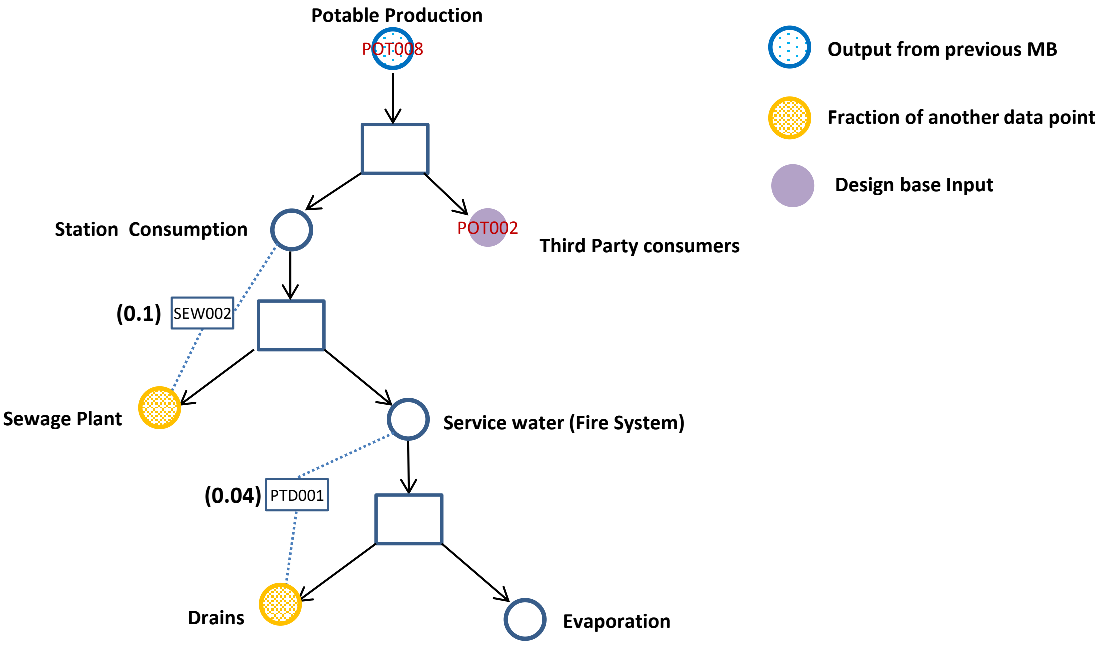


Figure 47: Identification of factor relationships (step 4)

The MB_IN and MB_OUT functions can be populated with the required outputs, as seen in Figure 48 below, in order to move down the potable system and establish a sequence for calculation.

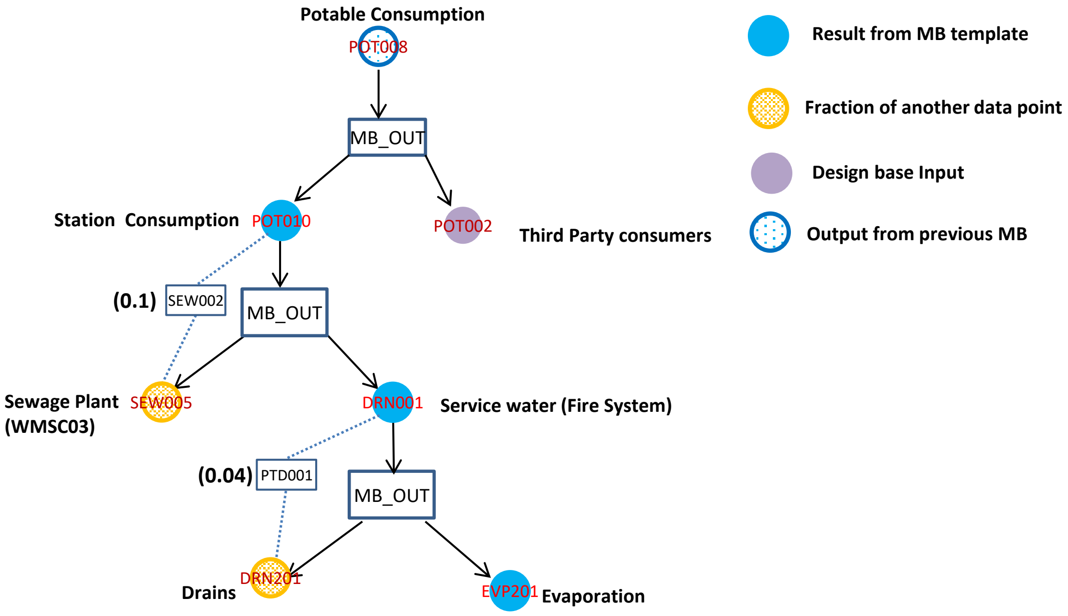


Figure 48: Identify the mass balance functions and calculate downwards (step 5)

It should be noted that the sequence of calculations should continue from the Demin plant, which ended at point 9 in Figure 43. Thus, the next design input is indicated as point 10. The potable consumption node calculated previously is carried down as point 4 and is illustrated in Figure 49.

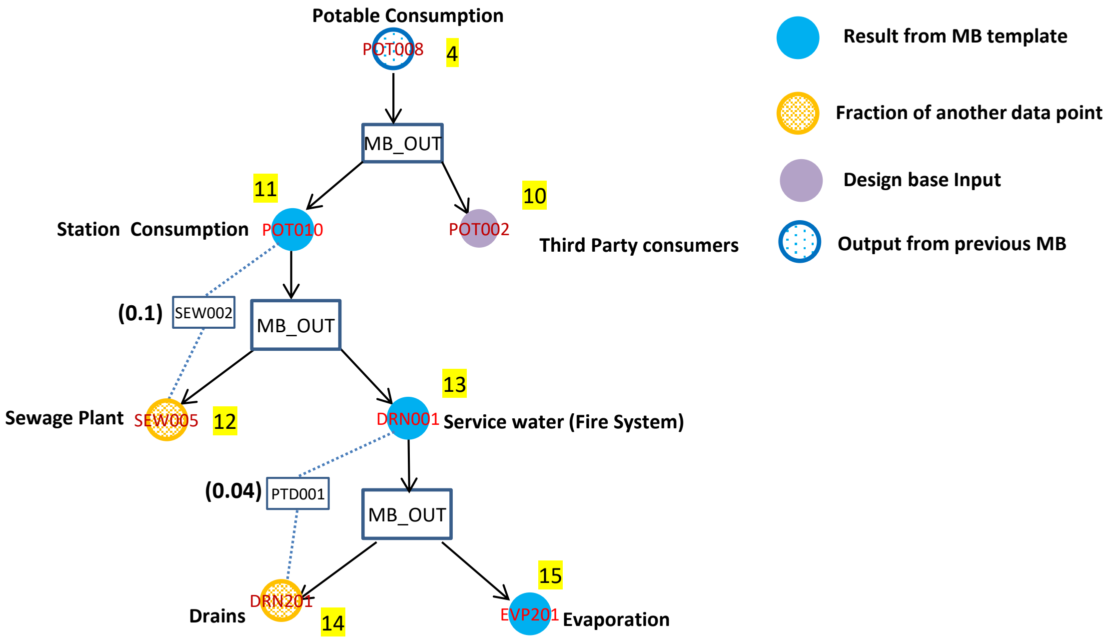


Figure 49: identify initialisation sequence (step 6)

3.2.3 Analytical model verification

A full model validation is outside the scope of this dissertation due to the complexity of acquiring accurate reference data. The focus of this dissertation is on the development of a methodology to implement a water balance model and not the design of a new working Eskom model.

The sequence of calculations and various calculation templates were implemented analytically in Mathcad. Appendix A contains the comprehensive model of the design-based water balance for the selected power plant. The results of the complete model in Mathcad were not compared to that of the Excel model as significant changes were incorporated with the new methodology. The Demin and potable water calculations, as described above, can be seen in Appendix A.3. This model verified that the sequence of calculations as identified could indeed produce the required water balance results. The Mathcad model was used to verify the implementation of the water balance calculations on EtaPRO.

3.3 Water balance development for the remaining systems

3.3.1 Cooling water system

Figure 50 illustrates the schematic for the cooling water system.

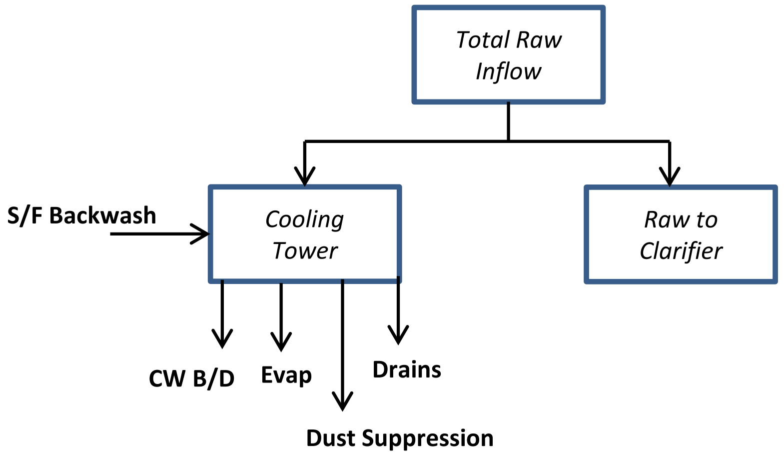


Figure 50: Schematic of CW system

Figure 51 shows the water balance network for the CW system.

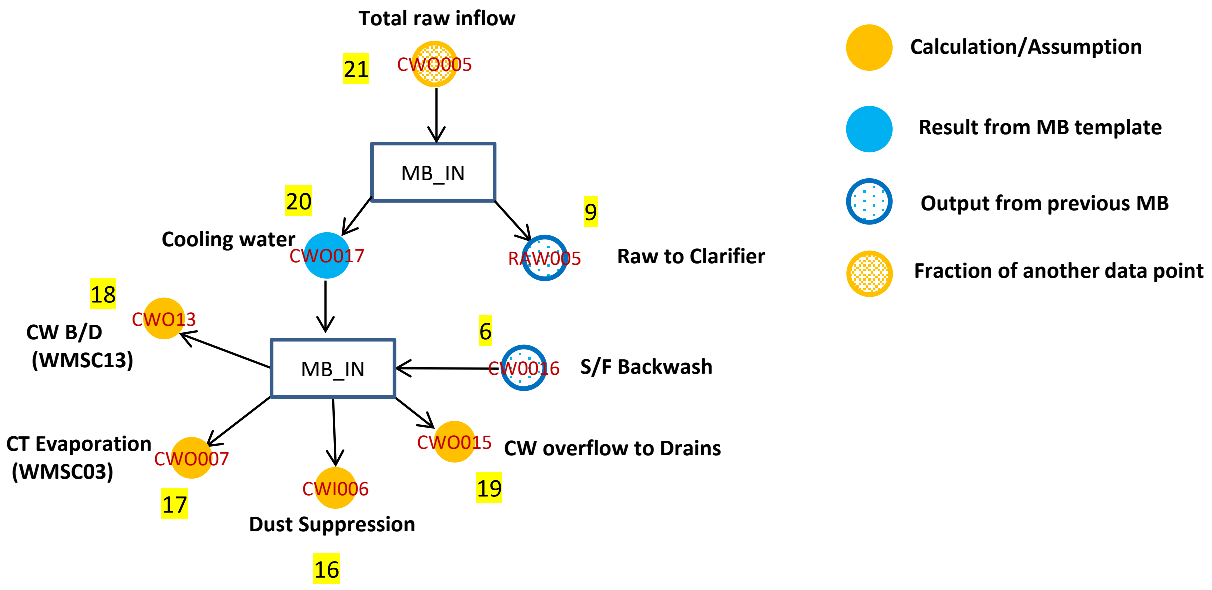


Figure 51: Water balance model for CW system

The main output streams of the CW system are the CW blowdowns (node CWO13) and cooling tower evaporation (node CWO007). However, water is also withdrawn for dust suppression (node CWI006) in the power plant selected, and a portion of water is lost due to CW overflow (node CWO015) which is released to the station drains.

The quantity of water used for dust suppression was estimated based on historically logged values due to the lack of flow meters. The dust suppression water taken from the CW system and filled into water tankers is sprayed onto the Coal Stock Yard. The dust suppression volume was calculated by knowing the number of times the water tankers were filled in a day and the capacity of the tankers.

The backwash flow is a known output from the previous mass balance calculations. The cooling tower evaporation is calculated using the design relationships in equations (14) and (15), and is captured in calculation template WMSC03 (Total make-up required by Cooling Towers) for node CWO007.

The equations in Section 2.8.3 were used to calculate the COC and the blowdown water from the CW system. The CW blowdown is calculated using equation (25), which is defined as a calculation template WMSC13 (CW Clarifier Blowdown); while the COC can be calculated using template WMSC12 (COC). The theory on COC calculations were used to develop calculation template MWSC012 that incorporates Eskom specific water analysis.

As mentioned in Chapter 2, the cooling water accounts for approximately 90% of the total raw water consumption, and the potable and Demin water as 10% of the raw water, for the design case. By assuming that there is no CW overflow in the design case, the MB_IN function can be used to calculate the CW requirement at node CWO017. This deviates from the Excel model approach and is considered a more accurate method for the design case.

The CW requirement can be calculated using equation (57).

$$\dot{v}_{cw} = MB\_IN\left((\dot{v}_{bw}), \begin{bmatrix} \dot{v}_{BD.cw} \\ \dot{v}_{E.CT} \\ \dot{v}_{ds} \\ \dot{v}_{cw.overflow} \end{bmatrix} \right) \tag{57}$$

3.3.2 Sewage plant

Figure 52 indicates the sewage plant schematic and water balance model developed.

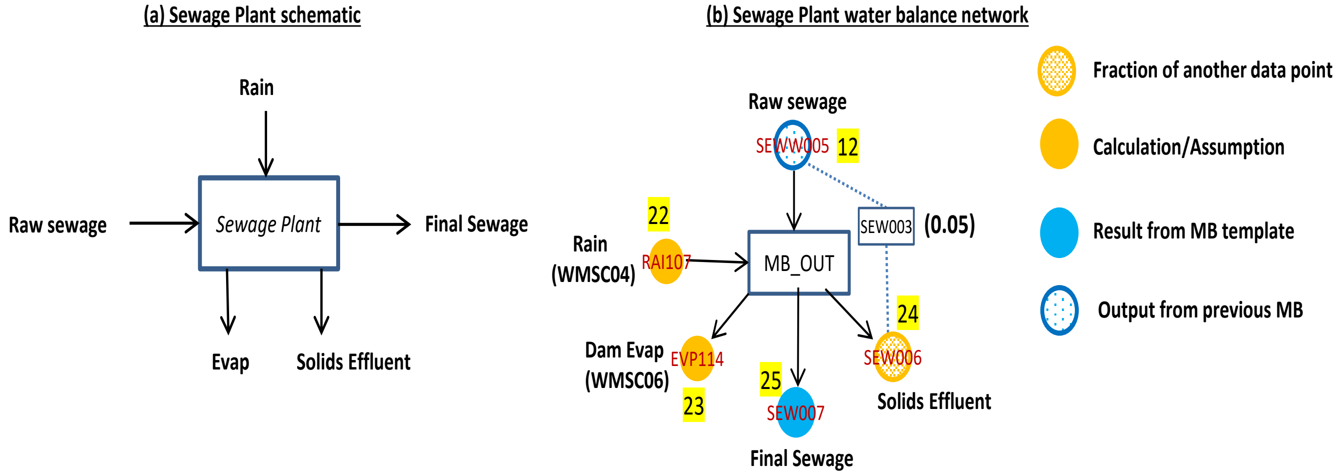


Figure 52: Sewage plant schematic and water balance model

The raw sewage, node SEW005, was calculated from the potable system balance and is now a known value. The solids discharge from the sewage plant, node SEW006, is an assumed factor of 5% of the raw sewage. This is from the Eskom Excel model based on the sewage plant design conditions. This value can be updated according to recently conducted plant performance tests. With the rainfall (node RAI107) and evaporation (node EVP114) points calculated through the calculation templates WMSC04 (rain collection ash dam pools) and WMSC06 (evaporation from ash dam pool) respectively, the final effluent sewage, at node SEW007, can be calculated as a MB_OUT calculation.

$$\dot{v}_{sew} = MB\_OUT\left(\begin{bmatrix}\dot{v}_{sew.in}\\ v_{r.sew}\end{bmatrix},\begin{bmatrix}e_{sew.corr}\\ \dot{v}_{sew.s}\end{bmatrix}\right) \tag{58}$$

Where:

$\dot{v}_{sew.in}$ = raw sewage inflow to the sewage plant (Ml/day)

$\dot{v}_{sew}$ = final sewage outflow of the sewage plant (Ml/day)

$\dot{v}_{r.sew}$ = rain water collection on the sewage maturation pond (Ml/day)

$e_{sew.corr}$ = evaporation from the sewage maturation pond (Ml/day)

$\dot{v}_{sew.s}$ = discharge due to solids removal from the sewage plant (Ml/day), calculated as 5% of $\dot{v}_{sew.in}$

The Excel model did not account for rainfall and evaporation from the sewage maturation pond and this was included as an improvement to the overall water balance methodology.

3.3.3 Coal Stock Yard

The Coal Stock Yard (CSY) schematic and water balance model can be seen in Figure 53.

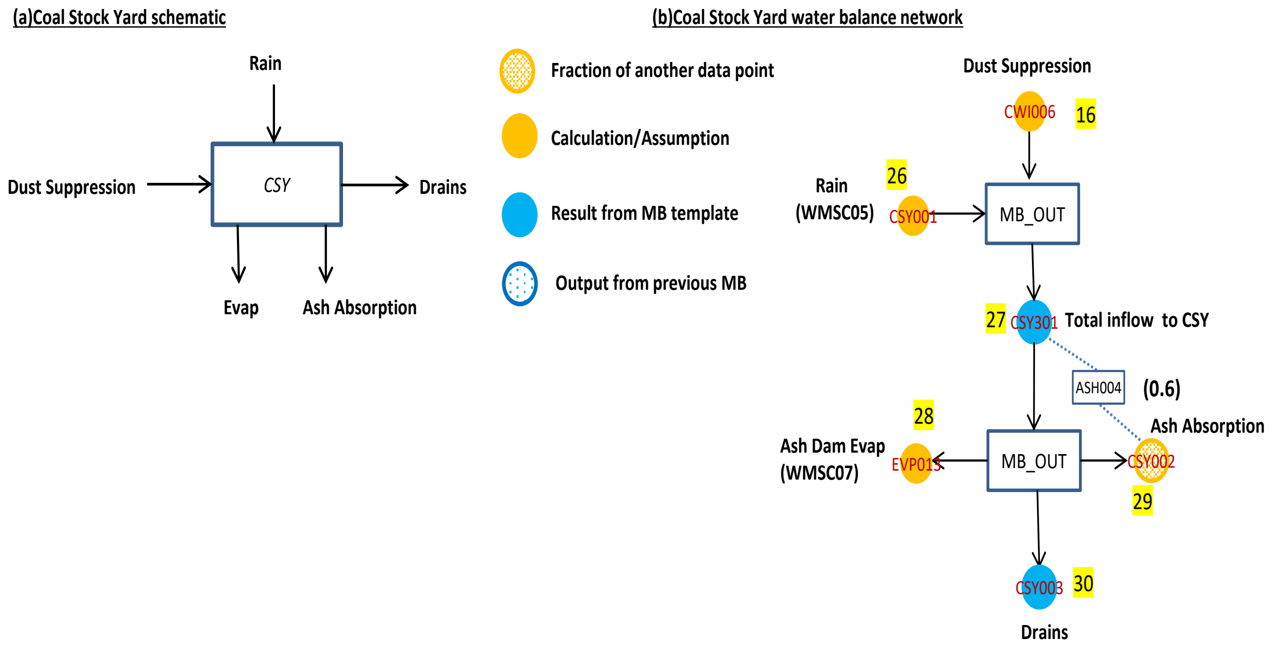


Figure 53: CSY schematic and water balance model

The Excel model did not account for water lost through ash absorption (node CSY002) on the CSY. This was added to the new model development as an additional loss from the system. The AIH value of 60% used in the Excel model and verified was used as a factor relationship with the total volume of water.

The CSY receives rainwater (node CSY004) and dust suppression water (CWI006) as inflows. The AIH value of ash was used as a factor of the total incoming streams to produce the ash absorption loss. Hence, an additional mass balance step was created to define the total inflow water to the CSY mass balance. Node CSY301 is calculated using equation (59).

$$\dot{V}_{csy.in} = MB\_OUT\left(\begin{bmatrix}\dot{V}_{r.csy}\\ \dot{V}_{ds}\end{bmatrix},(0)\right) \tag{59}$$

The ash absorption is then calculated at node CSY002 using equation (60).

$$\dot{v}_{abs.csy} = \dot{v}_{csy.in} \cdot AIH \tag{60}$$

Once the mass balance is defined with known evaporation rates, the water outflow to the drains at node CSY003 can be calculated using an outflow mass balance calculation using equation (61).

$$\dot{v}_{csy.drain} = MB\_OUT\left((\dot{v}_{csy.in}), \begin{bmatrix} \dot{v}_{abs.csy} \\ \dot{v}_{E.csy} \end{bmatrix} \right) \tag{61}$$

3.3.4 Drainage system and ash plant

The drainage system depicted in Figure 54 (a) receives water due to Demin water drainage (node DEM006), potable water drainage (node DRN201), CW overflows (CWO015), CSY drainage (node CSY003) as well as run-off water from the station terrace (node RAI002).

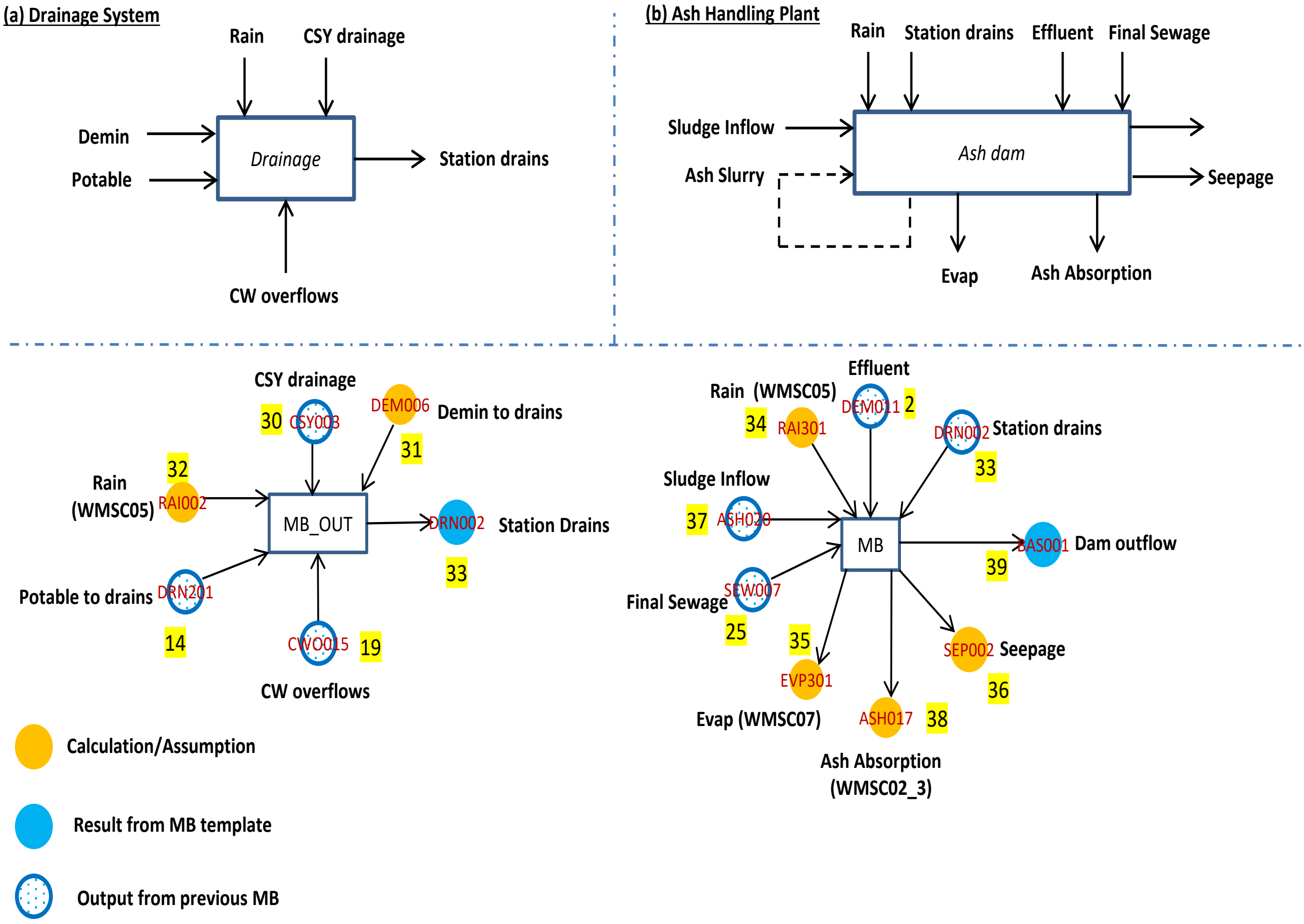


Figure 54: Ash plant and drainage system configuration and water balance

The loss of Demin water from the power plant to the drains is outlined by equation (41). The collection of water is conveyed to the ash dam system to be reused by the power plant ash handling system. The drainage system plays an integral role in the ash system balance. All the inputs are thus known allowing the user to calculate the total inflow to the drainage system by using equation (62) below.

$$\dot{V}_{st.drains} = MB\_OUT\left(\begin{bmatrix} \dot{V}_{csy.drains} \\ \dot{V}_{cw.overflow} \\ \dot{V}_{p\_drains} \\ \dot{V}_{dem\_drains} \\ \dot{V}_{r.terrace} \end{bmatrix}, (0)\right) \tag{62}$$

The ash system acts as the effluent sink for the power plant wastewater streams, therefore all blowdown water, WTP effluent generation, and final sewage is discharged to the ash dams.

The sluice water requirements determine the ash slurry from the power plant to the ash dam. The sluice water can be established by using ash to water ratios. The Excel model uses an ash to water ratio of 1:10 based on experimental and test data. This was confirmed by the zero liquid discharge reports for the power plant [95]. The ash content is calculated based on the as received coal quality. Thus, the volumetric flowrate of water required from the ash dam can be calculated. However, this is not required in the water balance calculation and is an internal calculation estimated for environmental reporting purposes on the ash dam capacity requirements and estimating the ash dam sinking capability.

The water loss on the ash dam consists mainly of evaporation, ash absorption, bottom ash quenching, and ash seepage. The ash absorption is calculated using the AIH value explained in Chapter 2. This correlates well when calculated based on the drainage principles of ash dams and the ZLD study conducted on the chosen site [95].

The ash dam system accounts for a large portion of the rainwater collection and evaporation due to its large surface area. The rainwater accumulation is calculated using run-off factors based on the ash dam configuration defined by equation (36), while evaporation is calculated using the ash phase evaporation rate in equation (38).

It should be noted that each power plant consists of a varying number of dams. Hence, the rainfall and evaporation shown as a single data point would be defined by a summation of all the rainfall and evaporation on the dams.

The ash system makes use of an MB_OUT calculation to estimate the outflow at node BAS001. Due to level control not considered in this model, the ash dam outflow is used as an indication of either a surplus or deficient of water on the ash dams.

The detailed calculation for all systems can be found in the Mathcad model in Appendix A.

3.4 Actual water balance framework development

The design water balance model is generally used to set an expected target for the actual water consumption on the power plant. The EtaPRO system contains real time plant data of various measurements from the plant historian. An actual water balance model can be developed using these known metered values as inputs. This can vary between power plants and therefore the model for the actual case is very specific to the data available for a selected power plant. In the description below, the approach taken for the actual case is to use the flow meters that most power plants would have available. The sections to follow are to illustrate the changes required from the design base model when including actual data sources and how this would be realised using the existing methodology.

3.4.1 Demin plant

The same plant configuration for the Demin plant in Figure 38 was used for the actual case. The first step will be to identify the metered inputs available and mark these with the relevant point ID as shown in Figure 55. In the actual case, the Demin consumption, Demin production, and potable production are all measured values. Note that the same naming convention can be used with the addition of “_ACT” to each point ID.

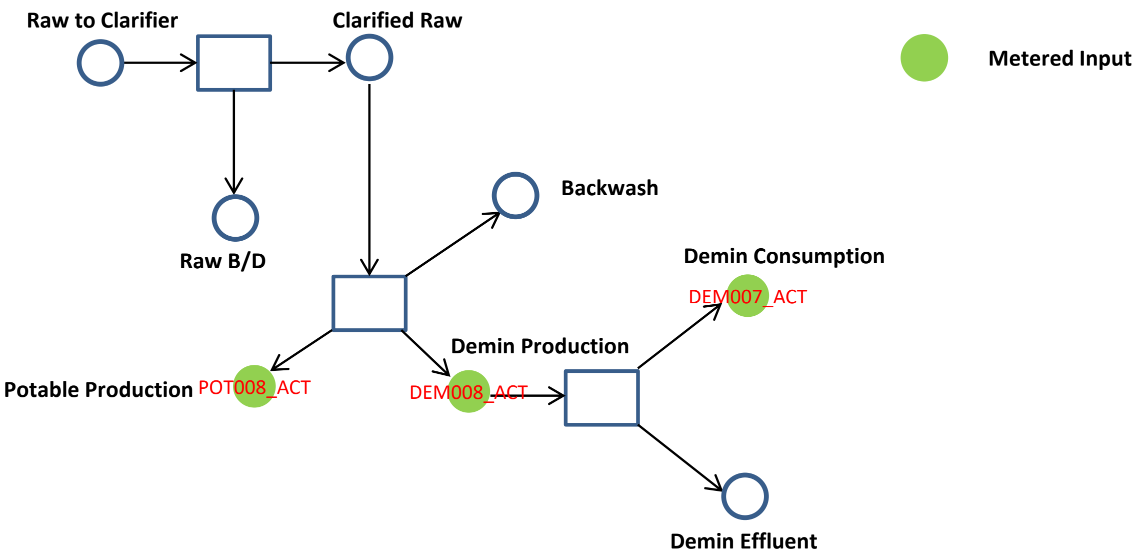


Figure 55: Actual metered input identification (step 1)

Similar to the design case, any calculations for data points should be marked with the template number. Due to two known points around the Demin production and consumption, the effluent template previously used in Figure 41 will not be required for the actual case. Also, note that the potable production node is no longer calculated using a factor. The more metered values that exist, the fewer assumptions or calculations will be required. In this case, only the raw clarifier blowdown still requires calculation.

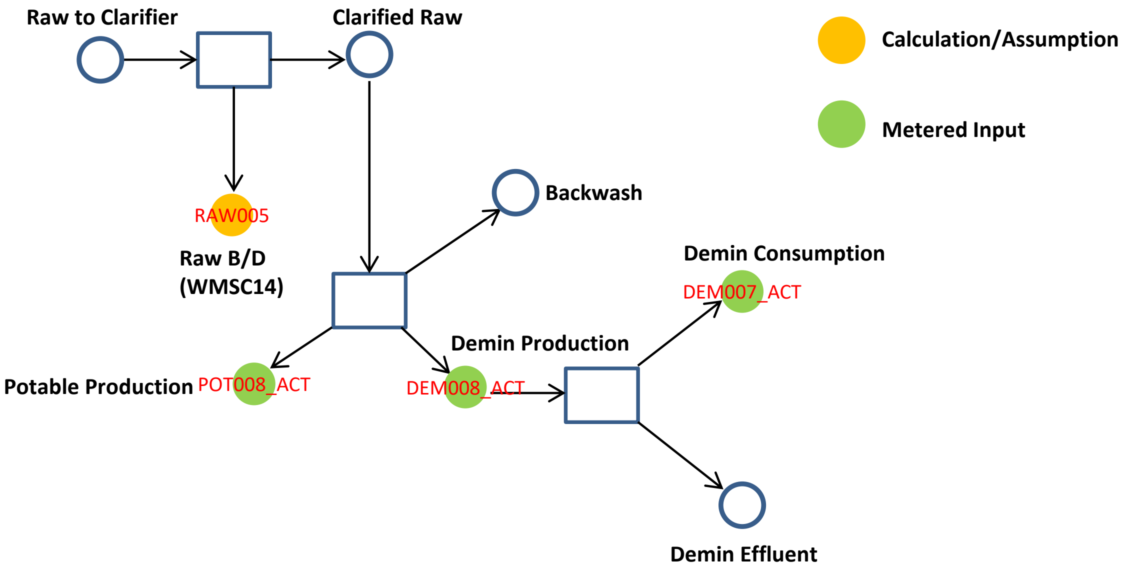


Figure 56: Calculation template identification for actual case (step 2)

Step 3 entails identifying any factor requirements and then the mass balance output nodes. It should be noted that the Demin effluent node has been converted into a mass balance output result.

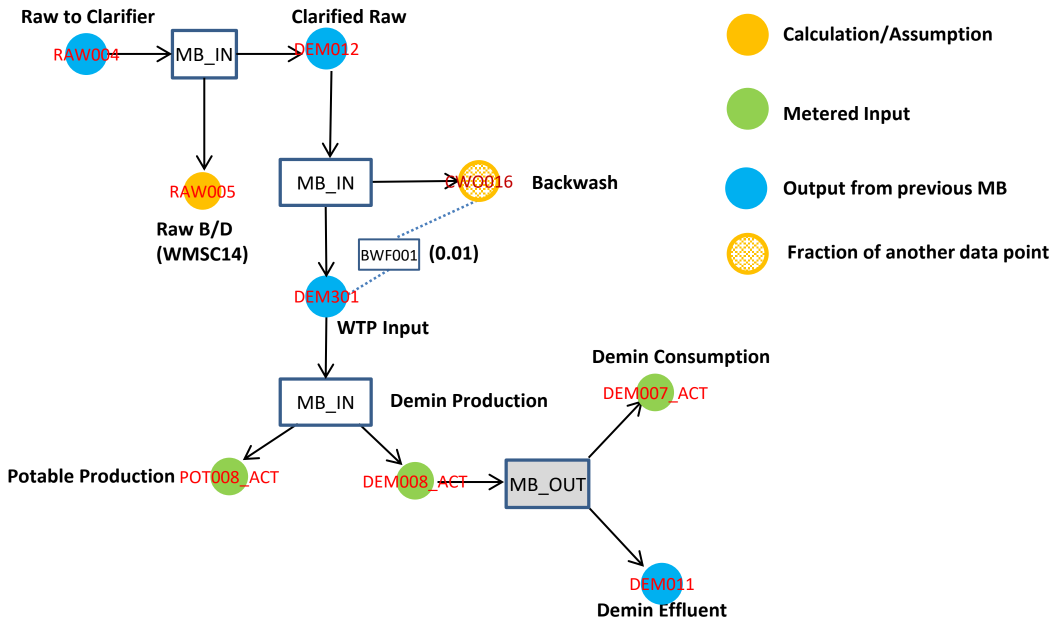


Figure 57: Factor and mass balance result identification (step 3)

Lastly, a new initialisation sequence can be established and is shown in Figure 58. This has changed from that of the design model in Figure 43.

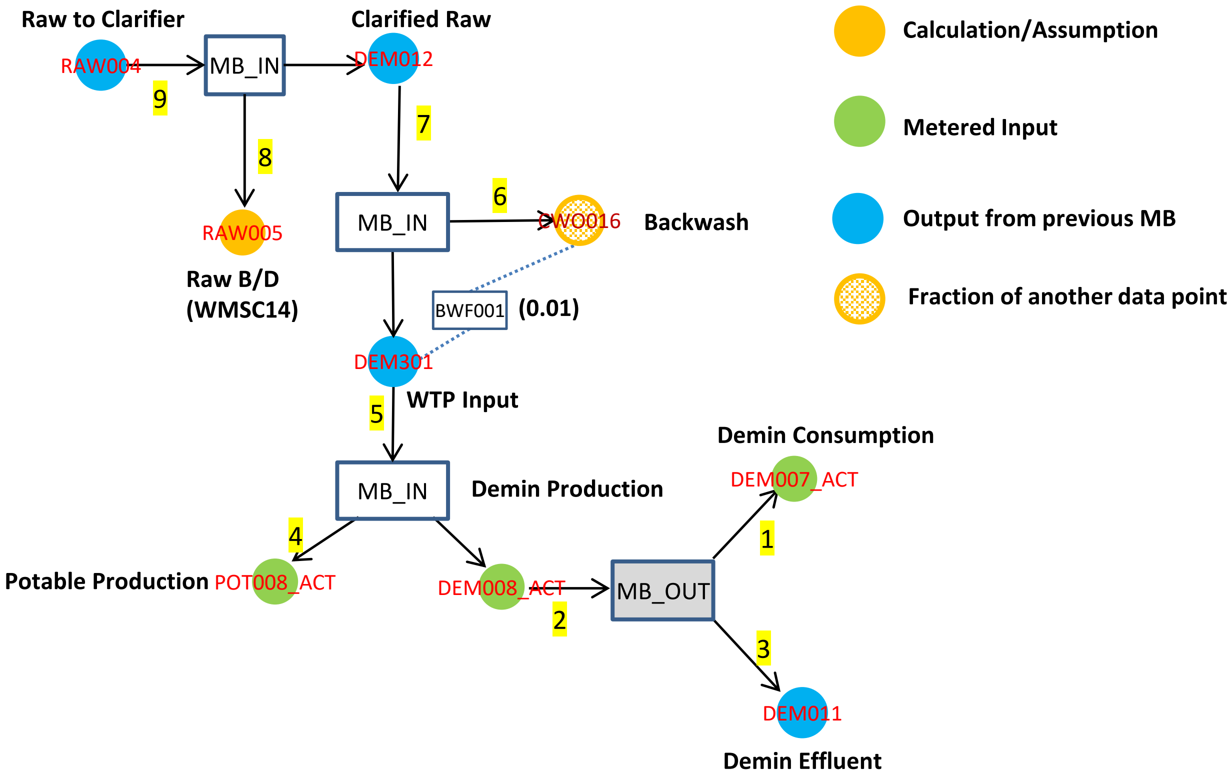


Figure 58: Initialisation sequence for actual case on Demin plant

3.4.2 Potable water plant

A similar approach was applied to the potable system. The metered values are indicated for the potable production, third party uses, and the firewater system. In some power plants, the potable water to the power plant may also be measured; in that case, there would be no need for the mass balance to be performed. If a mass balance if performed, the result would be an indication of measurement inconsistencies. The factor for the potable water to raw sewage was removed due to the metered firewater available for the calculation. This also changes the initialisation order from the design case. Figure 59 illustrates the actual case for the potable plant.

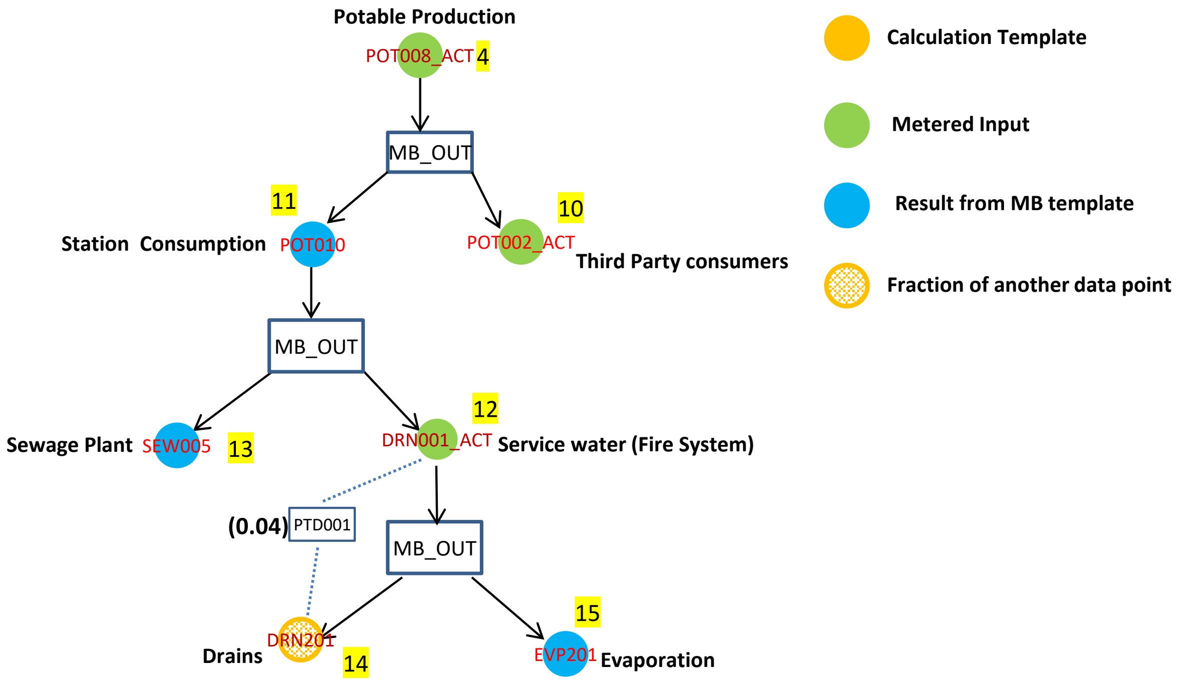


Figure 59: Actual water balance model for the potable system

3.4.3 Cooling water system

The only other system that requires a change in sequence due to possible availability of metered inputs is the CW system. The CW overflow at node CWO015 will change to an output of the MB_OUT calculation if node CWO017 is known. This would significantly improve the accuracy of the water balance model as this would account for approximately 90% of the raw water inflow and would be a recommended metered input. Figure 60 illustrates the actual case for the CW system.

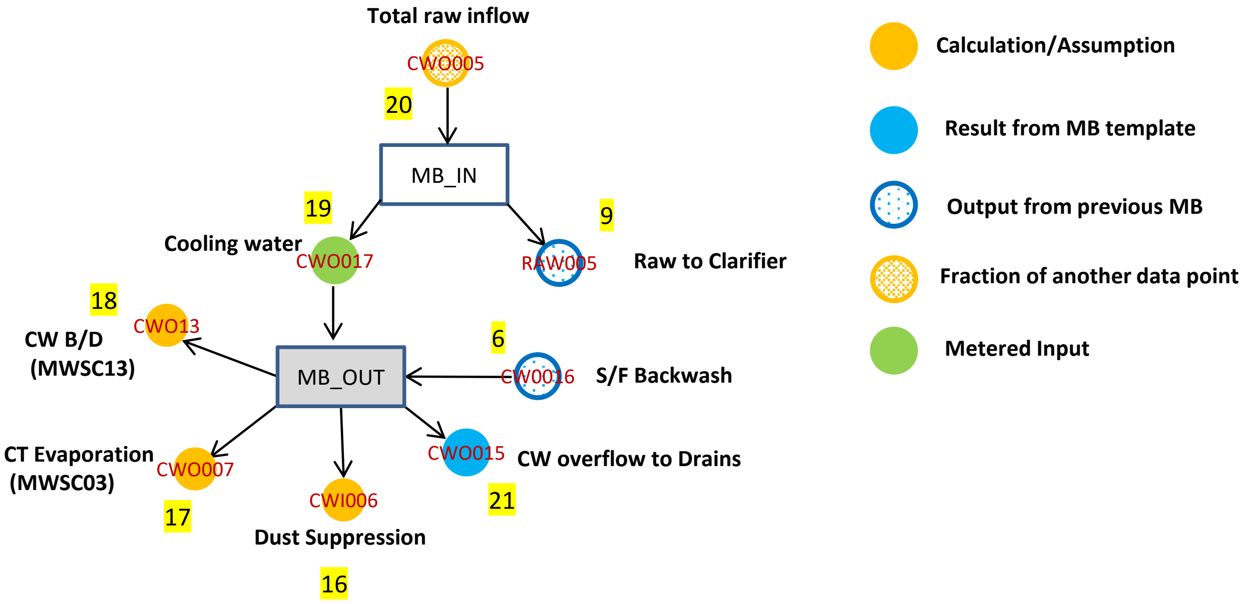


Figure 60: Actual case water balance model for the CW system

However, if node CWO017 is unknown, then the model remains the same as the design case. For the power plant selected in this dissertation, this is currently an unknown value.

The clarifier blowdowns are still calculated using calculation templates in the actual case. This can be improved if the number and duration of clarifier blowdowns are documented and used as manual inputs to account for the amount water lost at node CWO013 and node RAW005. This is available at certain power plants as a more accurate source of information, where no flow meters are available.

All other subsequent systems follow the same sequence of calculations as the design case due to the outputs of the Demin, potable and CW system being direct inputs into the sewage plant, drainage system, ash water and CSY system.

3.5 Data requirements and available sources

It should be noted that the measured values might vary between power plants; therefore, the methodology outlined can be used to establish the actual case for each power plant. Data can be retrieved from multiple sources and in varying forms. This section outlines the various sources and associated application.

Data sources:

- Flow meter readings can be either available locally (off-line), or in real time (available on the historian) and/or acquired data points on EtaPRO.

- EtaPRO has built-in calculations which can also be used as a data source. This includes STEP[1] or Virtual Plant outputs. STEP is a thermal evaluation tool used by Eskom to perform efficiency and energy loss calculations for all coal-fired plants in Eskom. The calculations are based on typical Rankine cycle thermodynamics and mass and energy balances.
- Chemistry data is available on software such as LIMs, which can be linked to EtaPRO as a future project.
- Ash system information is mostly available from environmental reports such as ZLD reports and the power plant water use licence.

Flow meter data requirements

Flow meter readings are the most accurate source of information for water systems. However, they are limited and pose a risk to achieve a fully operational water balance model. The flow meters that are most reliable and available at the power plants are Demin production/consumption, third party users, and potable production.

Demin consumption is available as real time data at all power plants and therefore makes a valid starting point for calculations. To improve an actual case mass balance, make-up flow to the CW system and raw water to clarifier, would have to be measured inputs as well. The factors used in the smaller streams can be determined by once-off measurements for validity.

Chemistry data requirements

Chemical analysis for water, coal, and oil are captured on a system called LIMs. The water analyses for the COC calculations are retrieved from this system. By using actual raw water quality data, an actual theoretical blowdown requirement can be estimated. This can also be compared to existing flow meters (if any) or logbook data.

EtaPRO data availability

All plant data that is available on the power plant historian system can be linked EtaPRO. EtaPRO then uses this data to perform mass and energy calculations on the overall thermal cycle. This data is mainly used for thermal efficiency calculations. However, the calculated heat rejection from the Rankine cycle and can be used for cooling tower evaporation calculations.

---

[1] STEP is a thermal evaluation tool used by Eskom to perform Efficiency and Loss calculations of coal-fired power plants. Calculations are based on a typical Rankine cycle thermodynamics and the mass and energy balances. Actual sensitivity analysis was performed during acceptance tests for all power plants and the results were used in calculations for parameter correlations and target settings.

The EtaPRO software uses the Turbine Cycle Heat Rate (TCHR) and a heat balance method over the turbine to calculate the heat rejection through the condenser. The TCHR is calculated as the ratio of heat input from the boiler to the turbine to the energy generated out of the turbine cycle. Virtual Plant, within the EtaPRO software, also calculates the heat rejection by the condenser using first principle mass and energy balances. This is achieved by calculating the steam cycle enthalpy drop across the condenser. The enthalpy drop is obtained by using saturated liquid conditions at the condenser outlet, and the conditions at the turbine outlet, by using the condenser pressure and isentropic turbine efficiency. The heat rejection from Virtual Plant is then used to estimate the cooling water flowrate. The cooling water flowrate and condenser temperature rise can be used in equation (13) as another alternative for evaporation losses. The details of the calculations performed in EtaPRO are available in the EtaPRO Calculation Template manual [98].

The STEP tool, which is available on EtaPRO, is used to account for efficiency losses and gains, and to provide additional data that can be used in the water balance model. It should be noted that STEP values are reported on a monthly basis. Due to these built-in functions, the following data mentioned in Chapter 2 and Chapter 3 can be retrieved:

- Unit Sent Out ($\dot{W}_{net}$)
- Auxiliary power ($\dot{W}_{aux}$)
- Coal flow rate ($\dot{m}_{coal}$)
- Load factor (L_f)
- Actual Efficiency (η_a)
- Demin make-up ($\dot{v}_{dem}$)
- Coal qualities if online instrumentation is available (CV and ash content)
- Heat rejection to the cooling water ($\dot{Q}_{cw}$)
- Circulating cooling water mass flowrate ($\dot{m}_{cw}$)
- Condenser inlet and outlet temperatures ($T_{1.cw}, T_{2.cw}$)
- Climatic conditions such as dry-bulb and wet-bulb temperatures if a weather station is available (T_{db}, T_{wb})

EtaPRO consists of models for a design, target and actual case; therefore, the above values are also available for design and target cases. Where EtaPRO calculations are used, the calculations should be verified prior to use. The target case is important as Eskom sets specific performance targets for each power plant annually and monthly as Key Performance Indicators (KPIs). Once the framework for the design case has been established, this can also be used to establish a target case by replacing design inputs with target values.

In the target case, the window period for the water balance can be reduced to a month in order to evaluate monthly performance. Hence, the overall water balance framework should consist of a design, target, and actual case similar to existing models on EtaPRO. The data that exists on different time scales will require conversion to the same time scale for comparison at implementation stage.

3.6 Development of calculation templates in EtaPRO

The analytical model of the complete water balance was developed using Mathcad, and is shown in Appendix A. The Mathcad model was used as a reference to verify the implementation of calculation templates into EtaPRO.

A process had to be established for categorising the variables and equations based on EtaPRO functionality, thus Mathcad was used. The input variables defined in the Mathcad model was categorised as either a UDF or NV data point in EtaPRO.

NV data points were selected as data points that would be useful to generate different case studies such as weather data, design data, or acceptance test data. Data that also remains constant for long periods (exceeding 30 days) such as surface areas, raw water qualities or factors used in calculations, can also be NV data points as it allows the user the option to update the data in a more efficient manner. NV data records are mainly based on user requirements, which can vary between power plants.

Calculations can be performed using either UDF or calculation template selections. The flow chart illustrated in Figure 61 was utilised for the selection of which equations required calculation templates. It should be noted that all factors mentioned in section 3.2 and 3.3 are created via UDF calculations.

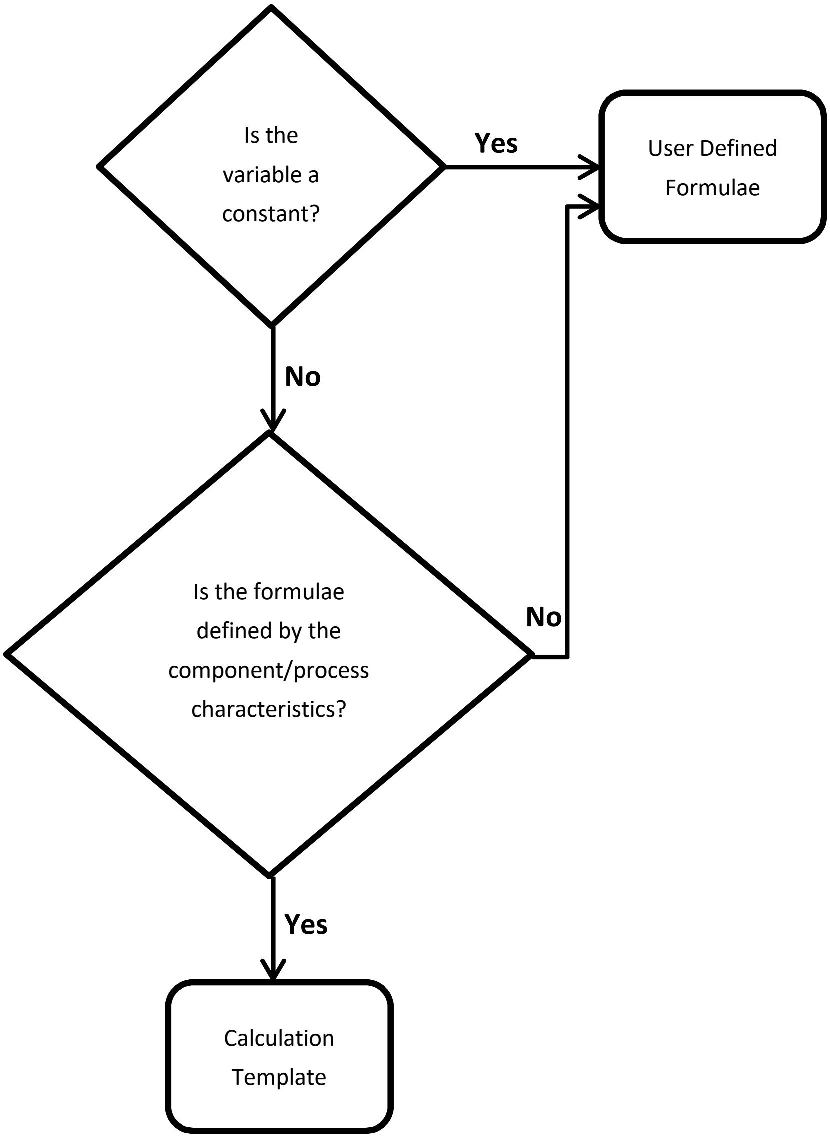


Figure 61: Flow chart for calculation template or UDF selection

The calculation templates selected are based on the mathematical definition of the process for a desired output. This allows templates to act as stand-alone process components that can be utilised to build several different water balance models according to varying plant configurations. This ensures minimum computational errors and offers a standardised approach to performing calculations. The objective of the template is to produce a desired process output by allowing the user to input a set of data points. For the water balance model development, 19 calculation templates were identified and developed in EtaPRO. The list of the templates is indicated in Table 8 with their defining equations attached in Appendix B.

Table 8: List of Calculation Templates developed in EtaPRO

Point ID	**Description**	**Engineering Units**
WMSC01	Station Sent Out (SSO)	GWh
WMSC02	Mass of total ash produced	t(SI)
WMSC02_1	Volume of total ash produced	ML
WMSC02_2	Mass of coarse/Fly ash produced	t(SI)
WMSC02_3	Total water absorbed on ash dam	ML
WMSC03	Total make-up required by Cooling Towers	ML
WMSC04	Rain collection ash dam pools	ML
WMSC05	Rain run-off from Station terrace/ Ash Dam catchment	ML
WMSC06	Evaporation from Ash dam pool	ML
WMSC07	Evaporation form Ash Surface	ML
WMSC08	Evaporation from Coarse Ash Quenching	ML
WMSC10	Design Water Performance	ML
WMSC12	COC	NA
WMSC13	CW Clarifier Blowdown	ML/d
WMSC14	Raw Clarifier Blowdown	ML/d
WMSC15	WTP total effluent	ML/d
WMSC18	Total water required for Ashing	ML/d
MBInCalc	MB Inflow	NA
MBOutCalc	MB Outflow	NA

3.6.1 Example calculation template: WMSC05 Rain run-off

Template WMSC05 was selected as the example to illustrate the methodology used to develop the templates. It represents the calculation of run-off water collection due to rainfall. The template structure is such that the inputs, calculations, and outputs can be clearly identified. Figure 62 shows the equation for the rainfall run-off water and the variables created respectively for capturing on EtaPRO. The reason for the variable name change is because EtaPRO requires data points to be described by a unique point ID that can consist of a combination of alphabetic and numeric characters.

Analytically in Mathcad:

Inputs:	**Calculation:**	**Output:**
f_r = run of factor i = avg rainfall A = surface area t = window period	$f_r \cdot i \cdot A \cdot t$	v_r Rain run-off from Station terrace/Ash Dam catchment

Translated in EtaPRO:

Inputs:	**Calculation:**	**Output:**
$FAC003\ [0-1]$ $RAI001\ [mm/day]$ $SAT001\ [hectare]$ $WPR001\ [day]$	$FAC003 \cdot RAI001 \cdot SAT001 \cdot WPR001 \cdot 0.01$	$RAI002\ [ML]$

Figure 62: Calculation template WMSC05 (Rainfall run-off) structure

Once the Mathcad model had been sectioned into UDF, NV data, or calculation templates, all variables were to be defined in accordance to the EtaPRO database requirements (point ID, description and engineering units). Engineering unit conversion factors were to be established at this point, where required. Conversion factors are employed when using Non-NIST engineering units in EtaPRO (or user specific engineering units). EtaPRO has conversion factors for NIST engineering units only. Thus, the EtaPRO calculation template does not perform unit conversion within formulas for Non-NIST engineering units. To ensure unit consistency and the correct engineering unit is output from the template, conversion factors were calculated for each variable in the equation.

Conversion steps:

$$V = (hectare)(mm/day)(day) = m^3$$

$$hectare = 10^4 m^2$$

$$mm = 10^{-3} m$$

$$m^3 = 10^{-3} ML$$

$$Conversion = (10^4)(10^{-3})(10^{-3}) = 0.01ML$$

Hence, there will be an additional correction factor of 0.01 added onto the Mathcad equation before the EtaPRO model development. Figure 62 is an example of the variable definition required and serves as an interface between the Mathcad model and the EtaPRO model. Table 9 is the setup of the variables used for the EtaPRO model development.

Table 9: Variable definition for EtaPRO model development for calculation template WMSC05

Point ID	Description	Engineering Units	Formula
User Defined Formula			
RAI001	Rainfall intensity	mm/day	1.963
SAT001	Station drainage surface area	ha	85.7
FAC003	Station terrace run-off factor	NA	0.726
WPR001	Window period	d	365
Calculation Templates			
WMSC05	Rain run-off from Station terrace	ML	(FAC003*RAI001*SAT001*WPR001)***0.01**

3.6.2 Calculation template development in C#

Once the calculation template nomenclature and architecture have been established, the calculation template can be developed using a programming tool, such as C#. The EtaPRO software is designed on the *.Net Framework* in C# programming language. The calculation template code was developed around the existing EtaPRO libraries on C#, such as the NVDataBase and the EtaPRO TemplateBase. A calculation template inherits its properties from the Abstract Class and TemplateBase using *GeneralPhysics.Applications.EtaPRO.PlugIn.dll*. The steps followed for the programming of the calculation template in C# programming software are outlined below.

Step 1: Create new project

The project titled Water Management System was created with two separate folders as indicated in Figure 63. The folders were created for water balance model templates (Calculations) and permanent point templates (PermPoints). Separate Class files were created for the description (Descriptions), point identity (IDs), engineering units (EngUnits), formulas description (Formulas), and NV data modules (PermData and PermData_COC) which are elements of a NV data record.

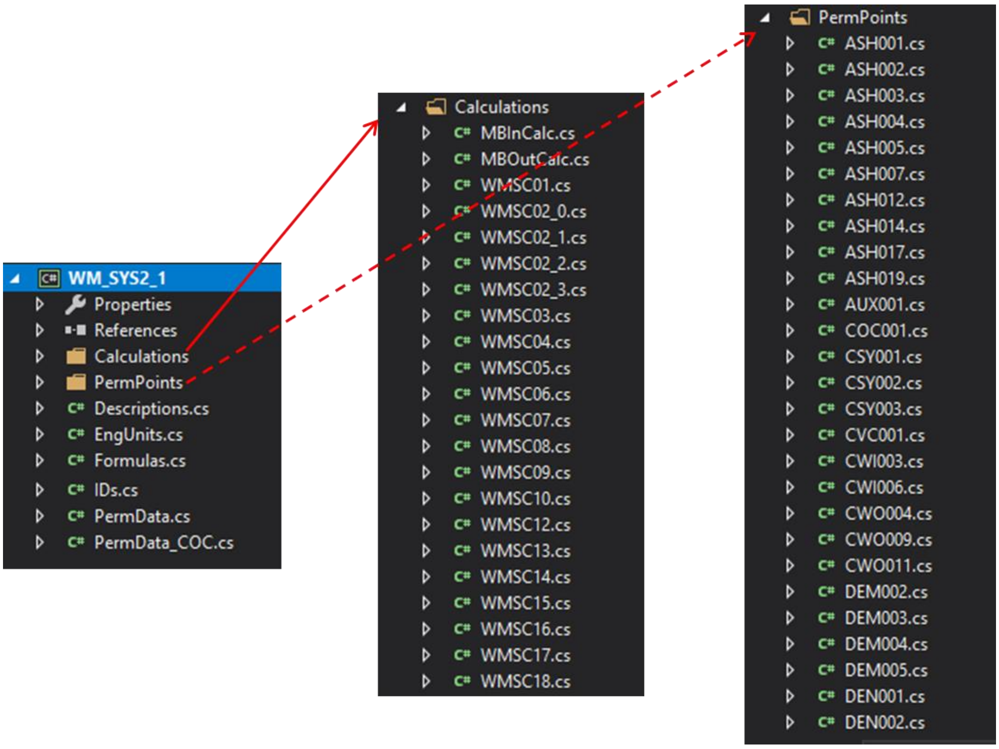
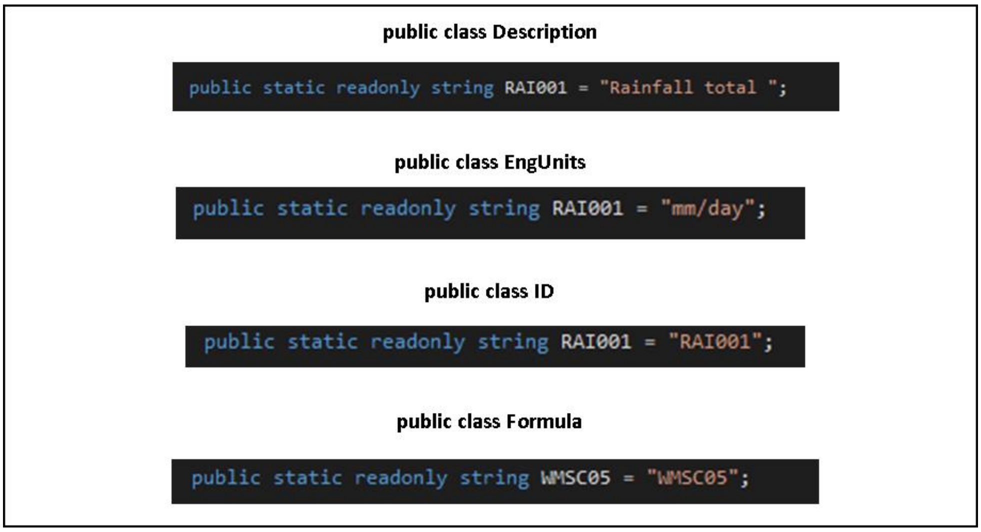


Figure 63: EtaPRO Water Management System project development

The Class files Descriptions, IDs, EngUnits, and Formulas are collections of the properties for each of the points required for the Water Management System project. An example of what is contained within these class files are illustrated with the variable RAI001 in Figure 64.



public class Description

```
public static readonly string RAI001 = "Rainfall total ";
```

public class EngUnits

```
public static readonly string RAI001 = "mm/day";
```

public class ID

```
public static readonly string RAI001 = "RAI001";
```

public class Formula

```
public static readonly string WMSC05 = "WMSC05";
```

Figure 64: Point properties in Class files

Step 2: NV record creation

The data structure of the Water Management System, illustrated in Figure 63, shows two Class files (PermData and PermData_COC) that are used for NV modules. The first Class file (PermData) was for the plant performance data (Water Management System) and the second Class file (PermData_COC) was for raw water quality (Water Management System Dosing).

Within each of the NV module are a collection of permanent points, called NV records, which the user can store for the creation of multiple cases. The code to create each record in a module is illustrated in Figure 65 with the data point RAI001.

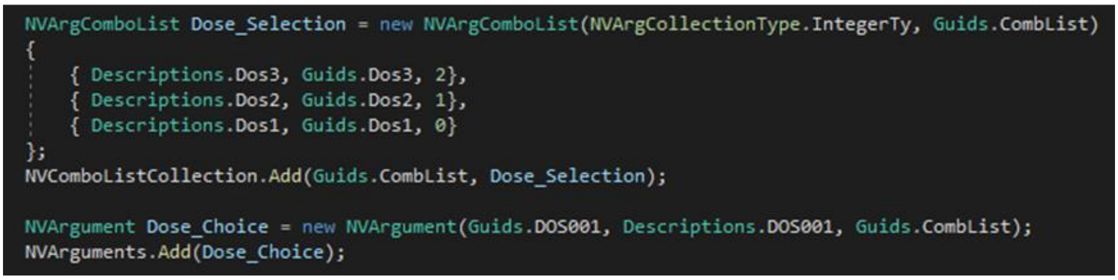
```
public class PermData : NVDataBase
{
    private NVArgument _RAI001;

private void InitializePermData()
{
    _RAI001 = new NVArgument(Guids.RAI001_perm, Descriptions.RAI001, PluginUnit.UnitEn.NO_UNITS, NVArgumentTypes.DoubleTy);
    NVArguments.Add(_RAI001);
```

Figure 65: NV record creation for RAI001

Similar to the *TemplateBase* class, the *NVDataBase* class requires you to first define the permanent points as *NVArguments*. Thereafter, the points must be initialised with point properties, and finally the points must be added to the *NVDataBase* object using the *NVArguments.Add()* method.

Raw water quality data was captured as a separate module (PermData_COC) as this data was not expected to change frequently. There can also be multiple raw water sources, where different cases may be required.

The method of chemical dosing at a power plant can vary between lime, acid or none. In order to allow the user to select a specific method of dosing, a drop-down selection was implemented for the dosing NV record. Figure 66 illustrates sections of the code used to develop the dosing selection in the NV record. This section of the code receives a value based on the user selection (0, 1 or 2) and then performs the calculation for the COC as per the dosing selection.



```
NVArgComboList Dose_Selection = new NVArgComboList(NVArgCollectionType.IntegerTy, Guids.CombList)
{
    { Descriptions.Dos3, Guids.Dos3, 2},
    { Descriptions.Dos2, Guids.Dos2, 1},
    { Descriptions.Dos1, Guids.Dos1, 0}
};
NVComboListCollection.Add(Guids.CombList, Dose_Selection);

NVArgument Dose_Choice = new NVArgument(Guids.DOS001, Descriptions.DOS001, Guids.CombList);
NVArguments.Add(Dose_Choice);
```

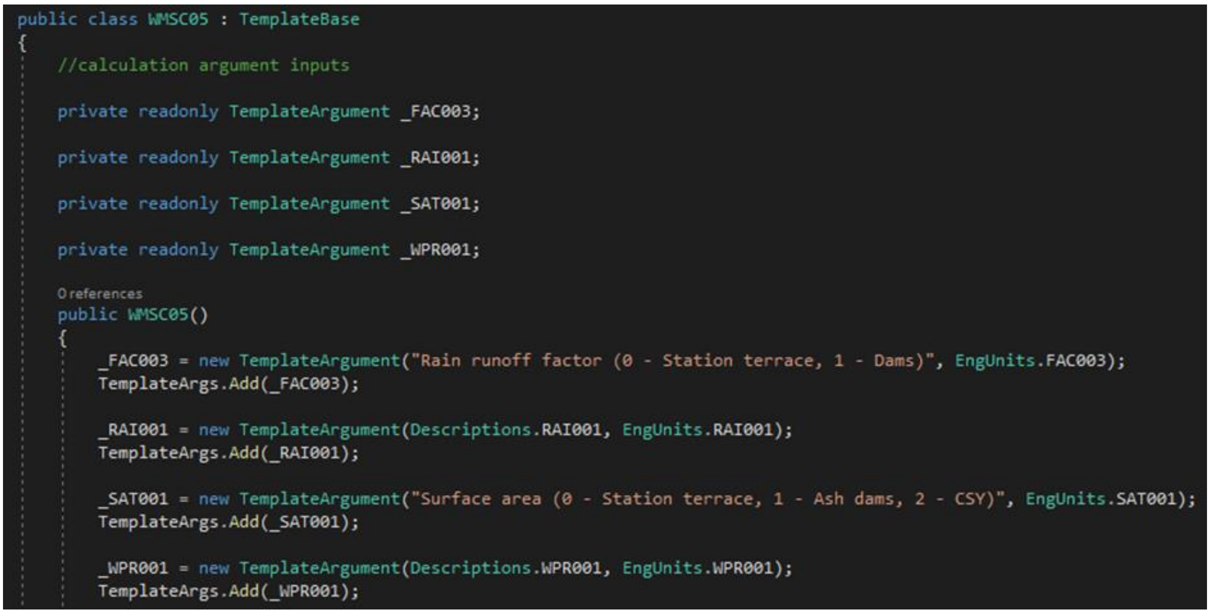
Figure 66: Specialised NV record creation for Water Management System Dosing

Step 3: Define inputs for calculation template

The structure to a calculation template contains a Constructor method and seven Virtual Override methods. These methods are:

- ID (point ID)
- Identity (SQL GUID)
- Description (point name)
- Units (engineering units)
- Formula (UI Display)
- NVData Association (SQL GUID pointing to the associated Non-Volatile Data)
- Calculate (C# code to be evaluated in the calculation engine).

To explain the structure of a calculation template, the WMSC05 Class file is used as an example. A code snippet of the constructor method for WMSC05 is illustrated in Figure 67.



```
public class WMSC05 : TemplateBase
{
    //calculation argument inputs

    private readonly TemplateArgument _FAC003;

    private readonly TemplateArgument _RAI001;

    private readonly TemplateArgument _SAT001;

    private readonly TemplateArgument _WPR001;

    0 references
    public WMSC05()
    {
        _FAC003 = new TemplateArgument("Rain runoff factor (0 - Station terrace, 1 - Dams)", EngUnits.FAC003);
        TemplateArgs.Add(_FAC003);

        _RAI001 = new TemplateArgument(Descriptions.RAI001, EngUnits.RAI001);
        TemplateArgs.Add(_RAI001);

        _SAT001 = new TemplateArgument("Surface area (0 - Station terrace, 1 - Ash dams, 2 - CSY)", EngUnits.SAT001);
        TemplateArgs.Add(_SAT001);

        _WPR001 = new TemplateArgument(Descriptions.WPR001, EngUnits.WPR001);
        TemplateArgs.Add(_WPR001);
```

Figure 67: Template WMSC05 Class development

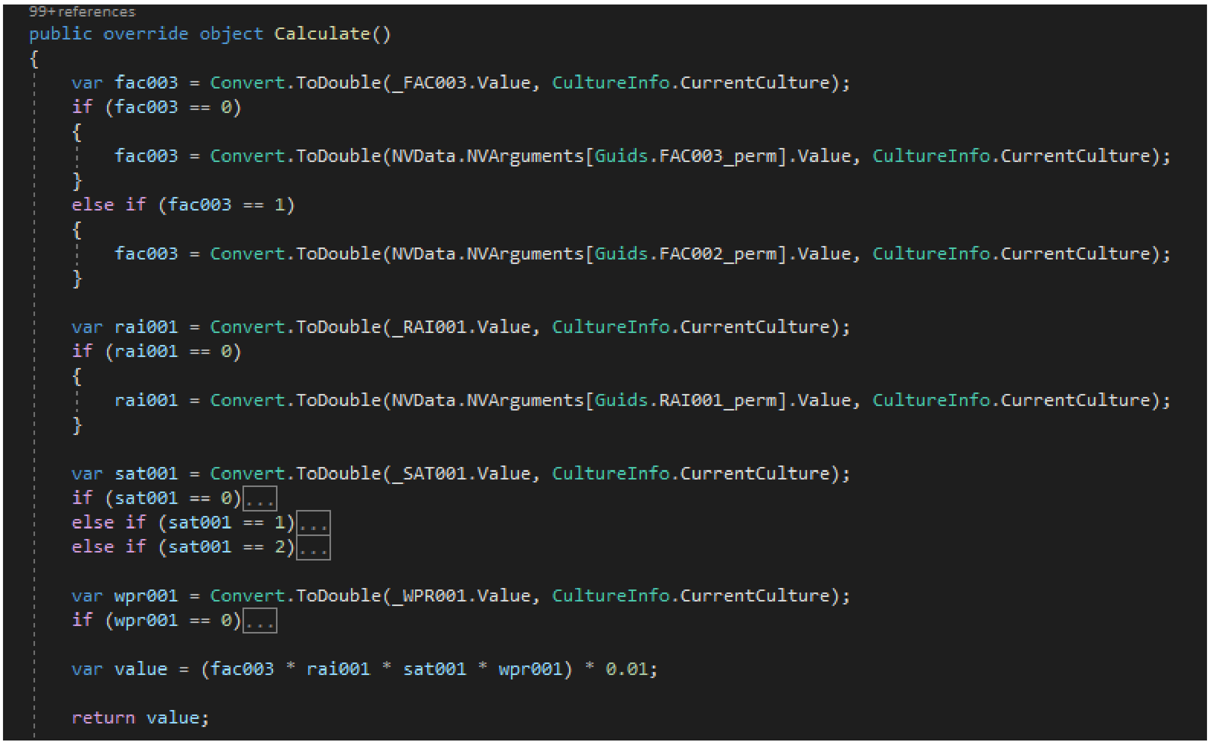
The *Constructor* method defines the inputs to the calculation template that will be used in the *Calculate* method to define the output. WMSC05 is defined as a *TemplateBase* object with its inputs, for example RAI001 is defined as a *TemplateArgument* object. The *TemplateBase* requires one to first define the *TemplateArgument* in its main Class definition. The Constructor method of *TemplateBase* is where the specific *TemplateArgument* is instantiated with its parameters defined. To finish the input creation, the *TemplateArgs.Add()* method is used to add the specified input to the templates definition.

Step 4: Define Calculate for calculation template

For the Calculate method of WMSC05, the following equation was computed for its output:

$$WMSC05 = RAI001 \cdot FAC003 \cdot SAT001 \cdot WPR001$$

In this calculation template, all the variables can be defined as permanent data and are all found in the NV module PermData. The code snippet for the Calculate method of WMSC05 is shown in Figure 68.

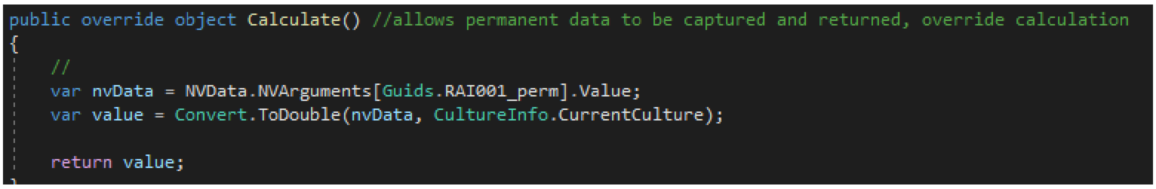


```
99+references
public override object Calculate()
{
    var fac003 = Convert.ToDouble(_FAC003.Value, CultureInfo.CurrentCulture);
    if (fac003 == 0)
    {
        fac003 = Convert.ToDouble(NVData.NVArguments[Guids.FAC003_perm].Value, CultureInfo.CurrentCulture);
    }
    else if (fac003 == 1)
    {
        fac003 = Convert.ToDouble(NVData.NVArguments[Guids.FAC002_perm].Value, CultureInfo.CurrentCulture);
    }

    var rai001 = Convert.ToDouble(_RAI001.Value, CultureInfo.CurrentCulture);
    if (rai001 == 0)
    {
        rai001 = Convert.ToDouble(NVData.NVArguments[Guids.RAI001_perm].Value, CultureInfo.CurrentCulture);
    }

    var sat001 = Convert.ToDouble(_SAT001.Value, CultureInfo.CurrentCulture);
    if (sat001 == 0)...
    else if (sat001 == 1)...
    else if (sat001 == 2)...

    var wpr001 = Convert.ToDouble(_WPR001.Value, CultureInfo.CurrentCulture);
    if (wpr001 == 0)...

    var value = (fac003 * rai001 * sat001 * wpr001) * 0.01;

    return value;
```

Figure 68: WMSC05 calculation development

At the start of the calculation code, the internal input variables (rai001, fac003, sat001 and wpr001) were created, and set to the value of an EtaPRO data point. A selection criterion was then used, in the form of *IF statements* based on the input value. If the input's value is 0, 1 or 2; a trigger is activated to collect the required NV data point and override the initial internal input value. The selection criterion allows one template to have multiple sources of inputs creating more flexibility. The calculation is performed using the set internal input values, and returns an output value.

The collection of calculation templates in the folder PermPoints were developed using the following Calculate method, seen in Figure 69. The function of this Calculate method is to retrieve the corresponding NV record and outputs the associated NV data value.



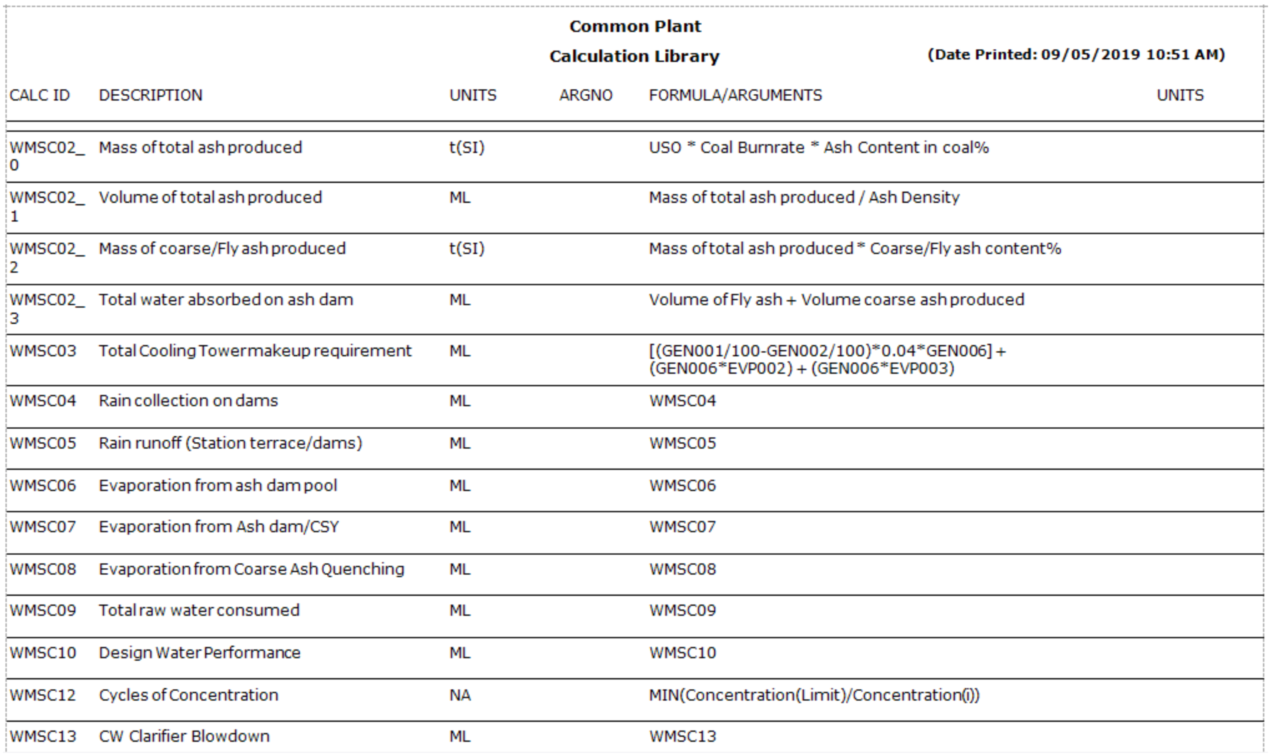
```
public override object Calculate() //allows permanent data to be captured and returned, override calculation
{
    //
    var nvData = NVData.NVArguments[Guids.RAI001_perm].Value;
    var value = Convert.ToDouble(nvData, CultureInfo.CurrentCulture);

    return value;
```

Figure 69: Calculation template development for permanent point RAI001

A single project was created in Visual Studios for all 19 templates. The details of each template can be found in Appendix B.

3.7 Water Management System development in EtaPRO Client

Ninteen calculation templates, permanent data points, and two NV data modules (one for the Raw Water quality only and another for all other NV data points) were created in Visual Studios using C# programming code. This was then uploaded into EtaPRO by stopping the server, uploading the plugin file (*WMS.PlugIn.dll*) under the debug folder, and pasting it into the EtaPRO program files folder and then restarting the server. Once the plugin is on the server it can be shared between all EtaPRO clients on the server. Figure 70 is a snapshot of some of the calculation templates created and available on EtaPRO Client for all users with the appropriate security privileges.



Common Plant

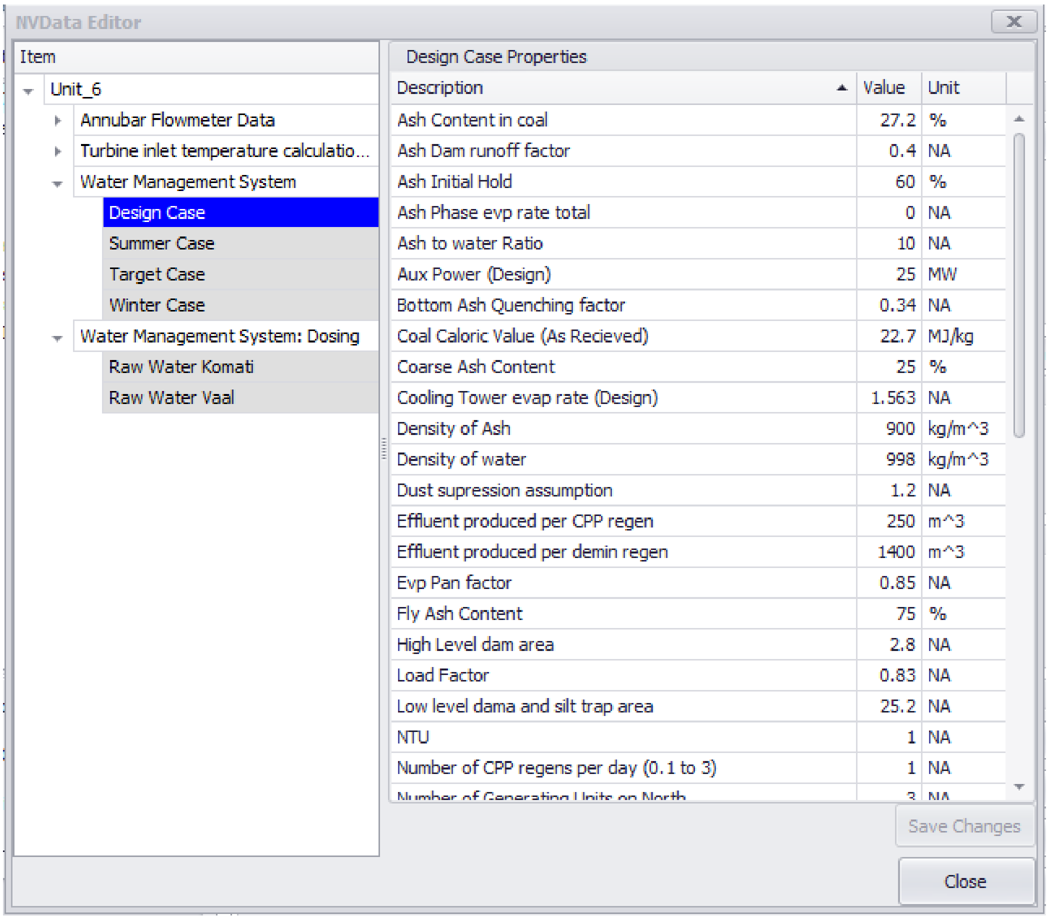
Calculation Library

(Date Printed: 09/05/2019 10:51 AM)

CALC ID	DESCRIPTION	UNITS	ARGNO	FORMULA/ARGUMENTS	UNITS
WMSC02_0	Mass of total ash produced	t(SI)		USO * Coal Burnrate * Ash Content in coal%	
WMSC02_1	Volume of total ash produced	ML		Mass of total ash produced / Ash Density	
WMSC02_2	Mass of coarse/Fly ash produced	t(SI)		Mass of total ash produced * Coarse/Fly ash content%	
WMSC02_3	Total water absorbed on ash dam	ML		Volume of Fly ash + Volume coarse ash produced	
WMSC03	Total Cooling Towermakeup requirement	ML		[(GEN001/100-GEN002/100)*0.04*GEN006] + (GEN006*EVP002) + (GEN006*EVP003)	
WMSC04	Rain collection on dams	ML		WMSC04	
WMSC05	Rain runoff (Station terrace/dams)	ML		WMSC05	
WMSC06	Evaporation from ash dam pool	ML		WMSC06	
WMSC07	Evaporation from Ash dam/CSY	ML		WMSC07	
WMSC08	Evaporation from Coarse Ash Quenching	ML		WMSC08	
WMSC09	Total raw water consumed	ML		WMSC09	
WMSC10	Design Water Performance	ML		WMSC10	
WMSC12	Cycles of Concentration	NA		MIN(Concentration(Limit)/Concentration(i))	
WMSC13	CW Clarifier Blowdown	ML		WMSC13	

Figure 70: Calculation library on EtaPRO Client

Figure 71 depicts the NV data base with all permanent points created for the user to now create multiple cases. In the Water Management System, four cases were created for the design, target, summer, and winter scenarios.

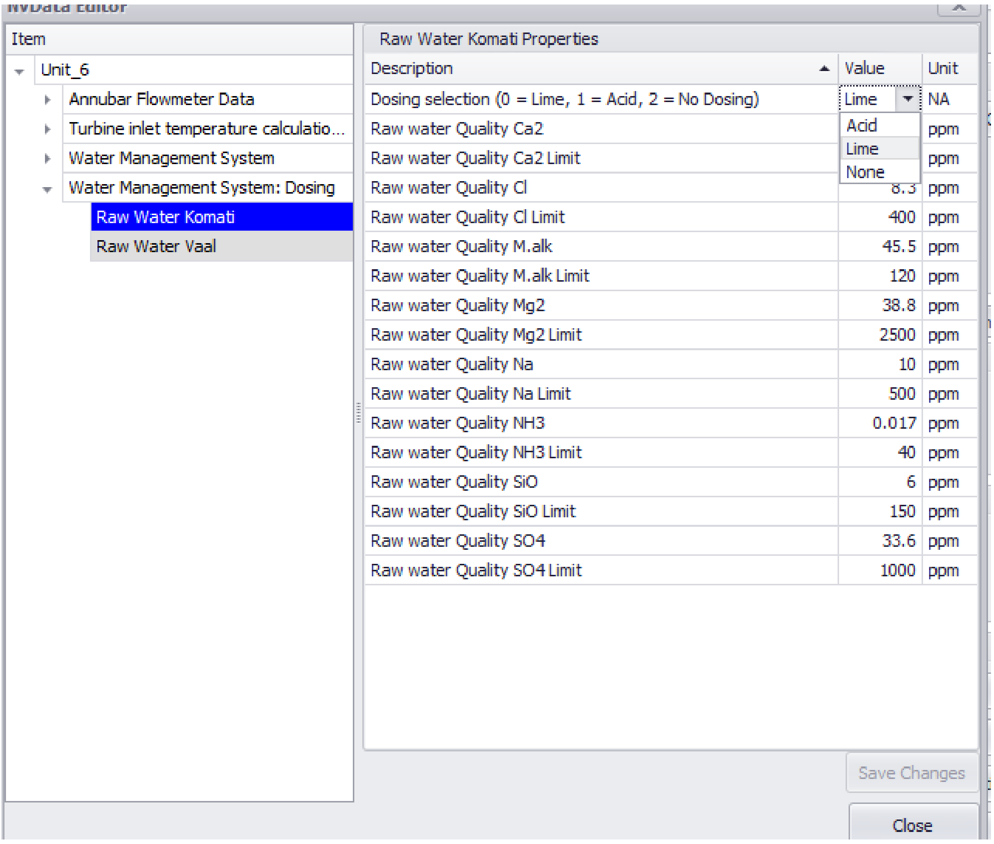


Design Case Properties

Description	Value	Unit
Ash Content in coal	27.2	%
Ash Dam runoff factor	0.4	NA
Ash Initial Hold	60	%
Ash Phase evp rate total	0	NA
Ash to water Ratio	10	NA
Aux Power (Design)	25	MW
Bottom Ash Quenching factor	0.34	NA
Coal Caloric Value (As Recieved)	22.7	MJ/kg
Coarse Ash Content	25	%
Cooling Tower evap rate (Design)	1.563	NA
Density of Ash	900	kg/m^3
Density of water	998	kg/m^3
Dust supression assumption	1.2	NA
Effluent produced per CPP regen	250	m^3
Effluent produced per demin regen	1400	m^3
Evp Pan factor	0.85	NA
Fly Ash Content	75	%
High Level dam area	2.8	NA
Load Factor	0.83	NA
Low level dama and silt trap area	25.2	NA
NTU	1	NA
Number of CPP regens per day (0.1 to 3)	1	NA
Number of Generating Units on North	3	NA

Figure 71: NV data records created with permanent data points

The Dosing NV record illustrated in Figure 72 consists of Komati and Vaal power stations’ raw water sources as an example. The drop-down menu for the dosing selection is also shown as an added functionality.



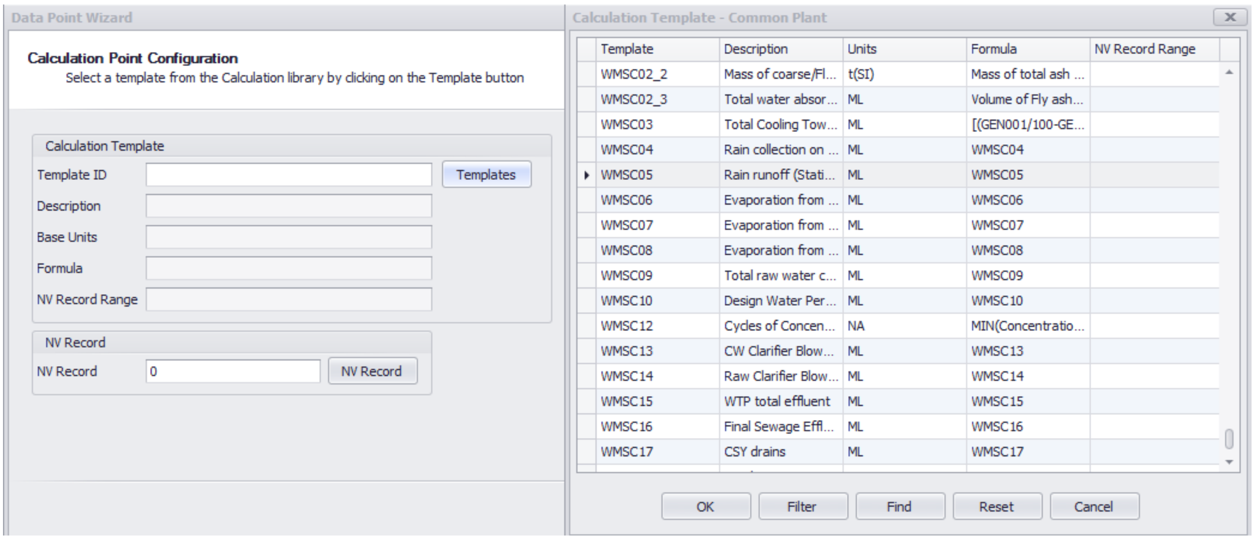
Raw Water Komati Properties

Description	Value	Unit
Dosing selection (0 = Lime, 1 = Acid, 2 = No Dosing)	Lime	NA
Raw water Quality Ca2		ppm
Raw water Quality Ca2 Limit		ppm
Raw water Quality Cl	8.3	ppm
Raw water Quality Cl Limit	400	ppm
Raw water Quality M.alk	45.5	ppm
Raw water Quality M.alk Limit	120	ppm
Raw water Quality Mg2	38.8	ppm
Raw water Quality Mg2 Limit	2500	ppm
Raw water Quality Na	10	ppm
Raw water Quality Na Limit	500	ppm
Raw water Quality NH3	0.017	ppm
Raw water Quality NH3 Limit	40	ppm
Raw water Quality SiO	6	ppm
Raw water Quality SiO Limit	150	ppm
Raw water Quality SO4	33.6	ppm
Raw water Quality SO4 Limit	1000	ppm

Figure 72: NV record for Dosing and Raw water quality

3.7.1 Using template MWSC05 to create an EtaPRO data point

To use the calculation templates created, the user will have to go to the Data Point Wizard on EtaPRO and select *calculation template* as the input method for the data point. Figure 73 shows the Point Configuration window and templates available for selection.

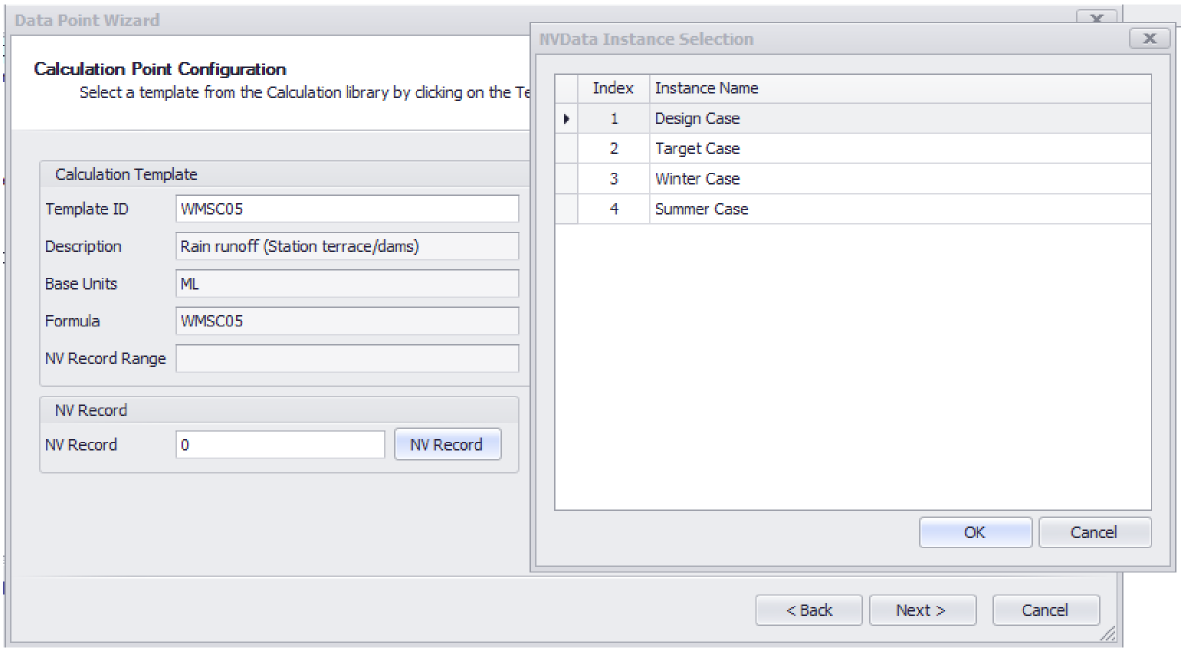


NV Record: 0

Template	Description	Units	Formula	NV Record Range
WMSC02_2	Mass of coarse/Fl...	t(SI)	Mass of total ash ...	
WMSC02_3	Total water absor...	ML	Volume of Fly ash...	
WMSC03	Total Cooling Tow...	ML	[(GEN001/100-GE...	
WMSC04	Rain collection on ...	ML	WMSC04	
WMSC05	Rain runoff (Stati...	ML	WMSC05	
WMSC06	Evaporation from ...	ML	WMSC06	
WMSC07	Evaporation from ...	ML	WMSC07	
WMSC08	Evaporation from ...	ML	WMSC08	
WMSC09	Total raw water c...	ML	WMSC09	
WMSC10	Design Water Per...	ML	WMSC10	
WMSC12	Cycles of Concen...	NA	MIN(Concentratio...	
WMSC13	CW Clarifier Blow...	ML	WMSC13	
WMSC14	Raw Clarifier Blow...	ML	WMSC14	
WMSC15	WTP total effluent	ML	WMSC15	
WMSC16	Final Sewage Effl...	ML	WMSC16	
WMSC17	CSY drains	ML	WMSC17	

Figure 73: Selecting a calculation template from the Calculation library

Template WMSC05 will be selected as the example illustrated thus far. Figure 74 illustrates how the Template ID, Description, Units and Formula have been updated according to the template code created. It also shows the NV record option where the user can now select cases based on the permanent data sets captured.



Template ID: WMSC05

Description: Rain runoff (Station terrace/dams)

Base Units: ML

Formula: WMSC05

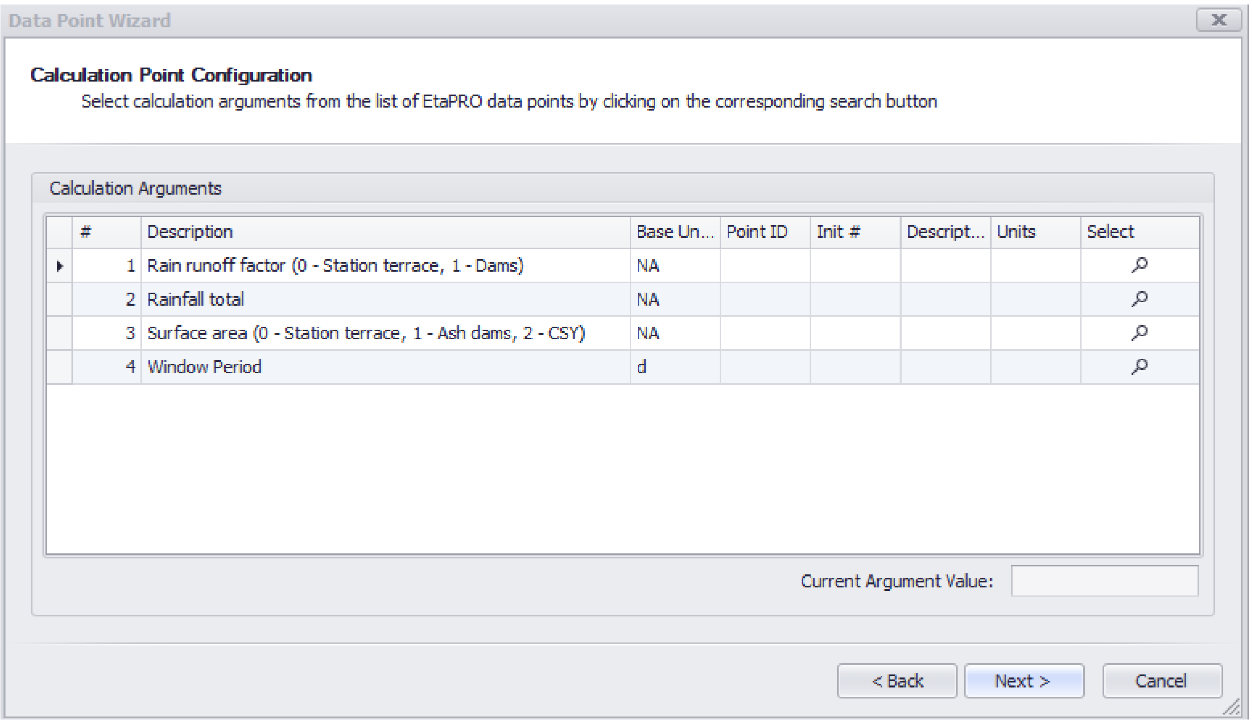
NV Record Range:

NV Record: 0

Index	Instance Name
1	Design Case
2	Target Case
3	Winter Case
4	Summer Case

Figure 74: NV record selection

The template will then require input arguments to be populated as per the code developed and shown in Figure 75. The first three columns are as per the template structure with argument number, description, and units respectively. The Point ID to be input can now be selected using the search column. All points to be used as inputs must already exist in the Point ID list on EtaPRO.



Select calculation arguments from the list of EtaPRO data points by clicking on the corresponding search button

#	Description	Base Un...	Point ID	Init #	Descript...	Units	Select
1	Rain runoff factor (0 - Station terrace, 1 - Dams)	NA					
2	Rainfall total	NA					
3	Surface area (0 - Station terrace, 1 - Ash dams, 2 - CSY)	NA					
4	Window Period	d					

Figure 75: Point configuration for MWSC05 with input requirements

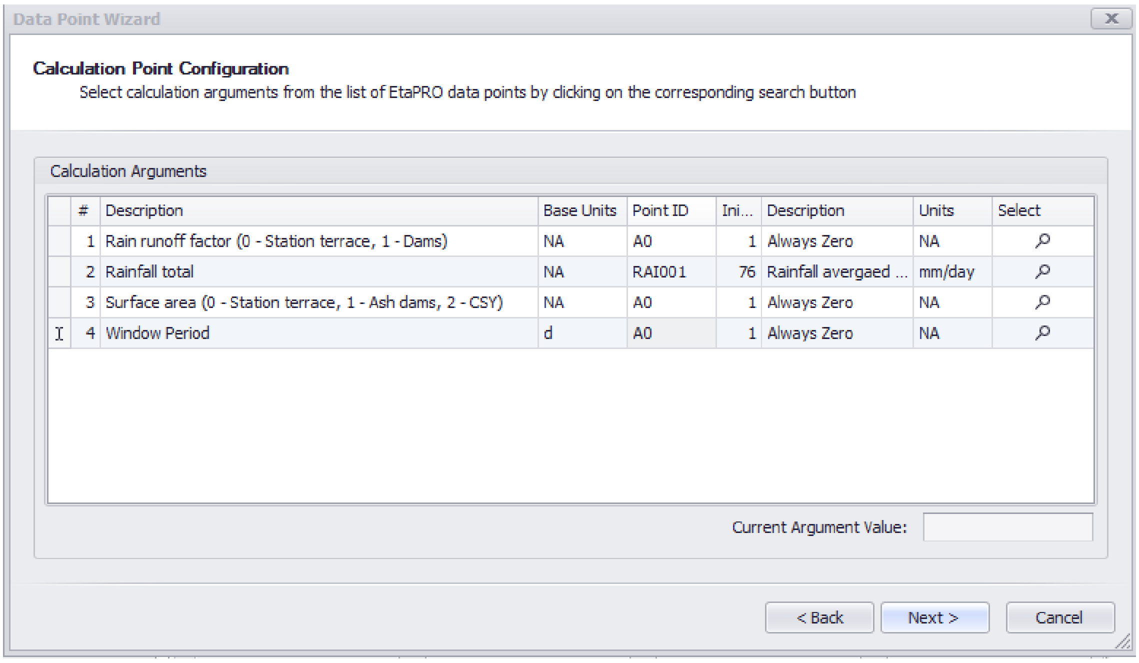
The template code was structured such that if the value of the selected point ID is zero, the code will use the value from the NV record selected. This allows the user to provide either an actual data measurement, or a default value.

The point configuration dialog box does not allow entering a number instead of a point ID, resulting in the creation of a few UDF data points that evaluate to a specific number. Tag number *A0* will always reports a value of “*0*”, while *A1* reports a value of “*1*”; this pattern will continue up to *A5*.

For the rain run-off factor input, two options are available based on whether the user is creating a point for a station terrace or a dam. This will be selected based on the user linking a point to data point *A0* or *A1*. In this example a *“0”* value was selected for a station terrace calculation.

A similar approach is taken for the surface area which is also selected as a *“0”* value for the terrace area. This allows the user to utilise one template for varying NV record values. The example shown in Figure 76 indicates data point RAI001 was created as a UDF and all other points are drawn from the NV record selected (Design Case) although RAI001 does exist as an NV data point. This was merely to illustrate that one can select an input as a UDF or NV data point or a combination of both in a single template.

The user is not forced to use the NV data points because they exist. The Init# (initialisation index) indicates the initialisation number of the Point ID selected, and represents the sequence of calculations. Data point RAI001 is at initialisation number “76” on EtaPRO and the other points indicate a value of “1” for first NV record selected.



Calculation Point Configuration

Select calculation arguments from the list of EtaPRO data points by clicking on the corresponding search button

#	Description	Base Units	Point ID	Ini...	Description	Units	Select
1	Rain runoff factor (0 - Station terrace, 1 - Dams)	NA	A0	1	Always Zero	NA	⚲
2	Rainfall total	NA	RAI001	76	Rainfall avergaed ...	mm/day	⚲
3	Surface area (0 - Station terrace, 1 - Ash dams, 2 - CSY)	NA	A0	1	Always Zero	NA	⚲
4	Window Period	d	A0	1	Always Zero	NA	⚲

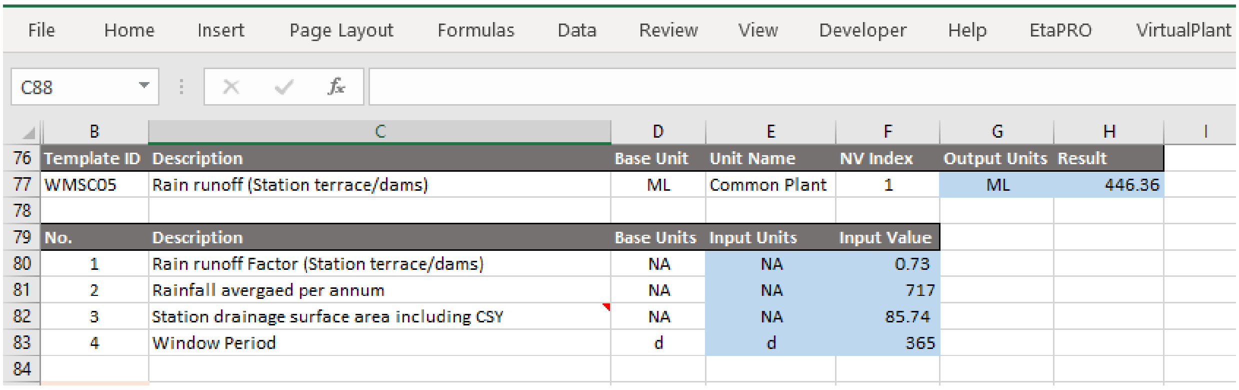
Figure 76: Calculation point configuration

Prior to the use of any tool, training should be provided to power plant personnel to familiarise themselves with the functionalities. This has been the approach in Eskom with the use of the current EtaPRO and Virtual Plant software in order to develop competent users of the software.

3.7.2 EtaPRO calculation validation

The validation process for the calculation templates were done using the Excel EtaPRO functionality. This feature allows one to call EtaPRO templates and read data point values from within the Excel environment. The same inputs used in the Mathcad model were entered into Excel. This can be seen in the screenshot in Figure 77. The output value of 446 ML displayed in column “H” and row “77” of the Excel screenshot in Figure 77 is exactly the same as that in the Mathcad calculation (see

Appendix A2), and therefore validates the WMSC05 template calculation and conversion factors used. This was done for all templates as part of the validation process.



Template ID	Description	Base Unit	Unit Name	NV Index	Output Units	Result
WMSC05	Rain runoff (Station terrace/dams)	ML	Common Plant	1	ML	446.36

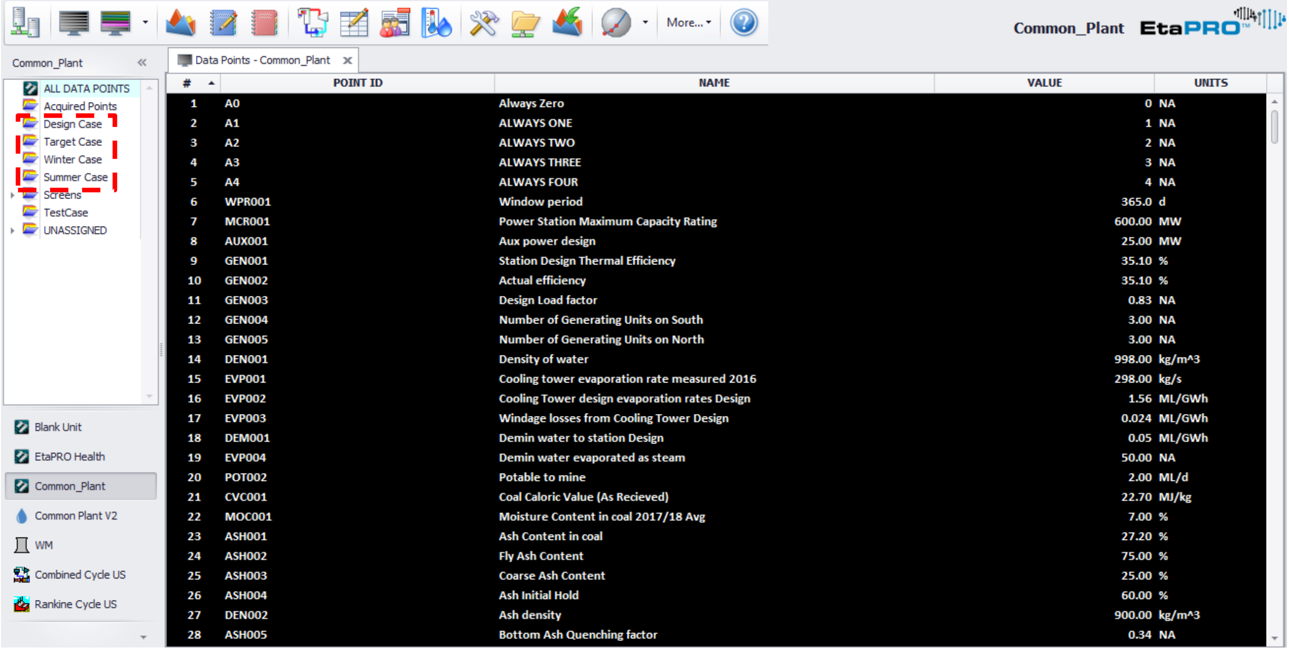
No.	Description	Base Units	Input Units	Input Value
1	Rain runoff Factor (Station terrace/dams)	NA	NA	0.73
2	Rainfall avergaed per annum	NA	NA	717
3	Station drainage surface area including CSY	NA	NA	85.74
4	Window Period	d	d	365

Figure 77: EtaPRO calculation template validation via Excel Add-In functionality

4. Implemented water balance model

4.1 Model results

The Mathcad water balance model was converted into UDF and calculation template data points, to set up a case study on EtaPRO. All the data points required to build the water balance model, as per the diagrams developed in Sections 3.2 to 3.4, were created on the EtaPRO Client system using both the newly defined calculation templates and UDF equations where needed. Figure 78 shows the Common Plant database created with data points from the water balance model in sequential order of calculation.



#	POINT ID	NAME	VALUE	UNITS
1	A0	Always Zero	0	NA
2	A1	ALWAYS ONE	1	NA
3	A2	ALWAYS TWO	2	NA
4	A3	ALWAYS THREE	3	NA
5	A4	ALWAYS FOUR	4	NA
6	WPR001	Window period	365.0	d
7	MCR001	Power Station Maximum Capacity Rating	600.00	MW
8	AUX001	Aux power design	25.00	MW
9	GEN001	Station Design Thermal Efficiency	35.10	%
10	GEN002	Actual efficiency	35.10	%
11	GEN003	Design Load factor	0.83	NA
12	GEN004	Number of Generating Units on South	3.00	NA
13	GEN005	Number of Generating Units on North	3.00	NA
14	DEN001	Density of water	998.00	kg/m^3
15	EVP001	Cooling tower evaporation rate measured 2016	298.00	kg/s
16	EVP002	Cooling Tower design evaporation rates Design	1.56	ML/GWh
17	EVP003	Windage losses from Cooling Tower Design	0.024	ML/GWh
18	DEM001	Demin water to station Design	0.05	ML/GWh
19	EVP004	Demin water evaporated as steam	50.00	NA
20	POT002	Potable to mine	2.00	ML/d
21	CVC001	Coal Caloric Value (As Recieved)	22.70	MJ/kg
22	MOC001	Moisture Content in coal 2017/18 Avg	7.00	%
23	ASH001	Ash Content in coal	27.20	%
24	ASH002	Fly Ash Content	75.00	%
25	ASH003	Coarse Ash Content	25.00	%
26	ASH004	Ash Initial Hold	60.00	%
27	DEN002	Ash density	900.00	kg/m^3
28	ASH005	Bottom Ash Quenching factor	0.34	NA

Figure 78: All data points created on EtaPRO system under a new Common Plant database

Part of the calculation template development was the development of permanent data sets (NV records and data points). The NV records that were shown in Figure 71 and Figure 72 were populated with data from the selected power plant. A design case NV record was created with all the input data required in accordance with the Mathcad model for the complete water balance development. This was used to link the calculation templates for the design case forming a fixed baseline for the water management system. Using the design case model with different NV records, a target, summer, and winter case was developed. The areas highlighted in a dashed box in Figure 78, shows how different models were developed in separate folders for the different cases.

The target values are based on pre-defined power plant performance targets. The target case was developed by entering in target values for load factor, Demin consumption, thermal efficiency, rainfall, evaporation, and coal quality as monthly averages.

The summer and winter cases were developed due to weather playing a crucial role in water consumption at a power plant. The winter case was developed by using the target case and adjusting the rainfall and evaporation rates based on the average recorded values for the summer months and winter months, respectively. The winter case serves as the best-case scenario with low evaporation rates and rainfall, and summer as the worst-case scenario with high evaporation rates and rainfall.

Once the various cases were developed, user screens, dashboards and trends were created using the EtaPRO functionality. Figure 79 displays what a typical screen would look like in EtaPRO for the water reticulation system. This allows for a quick overview of process operation and water distribution.

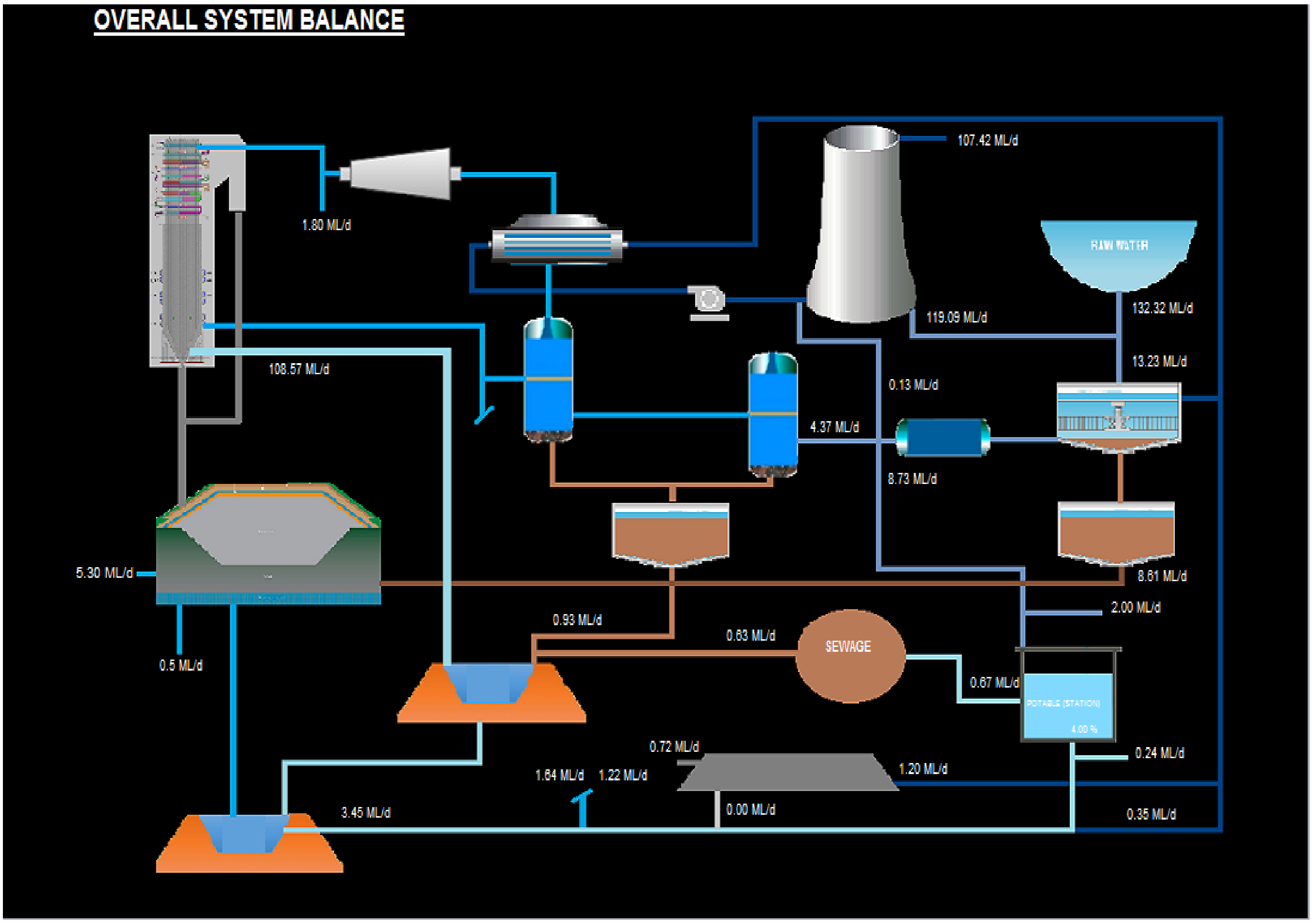


Figure 79: Overall system schematic (Design Case) on EtaPRO screen developer

Detailed sub-systems can also be developed to monitor specific process areas, such as Demin production as illustrated in Figure 80. All screens can be linked to one another allowing for ease of change from one system to another system by using interactive buttons.

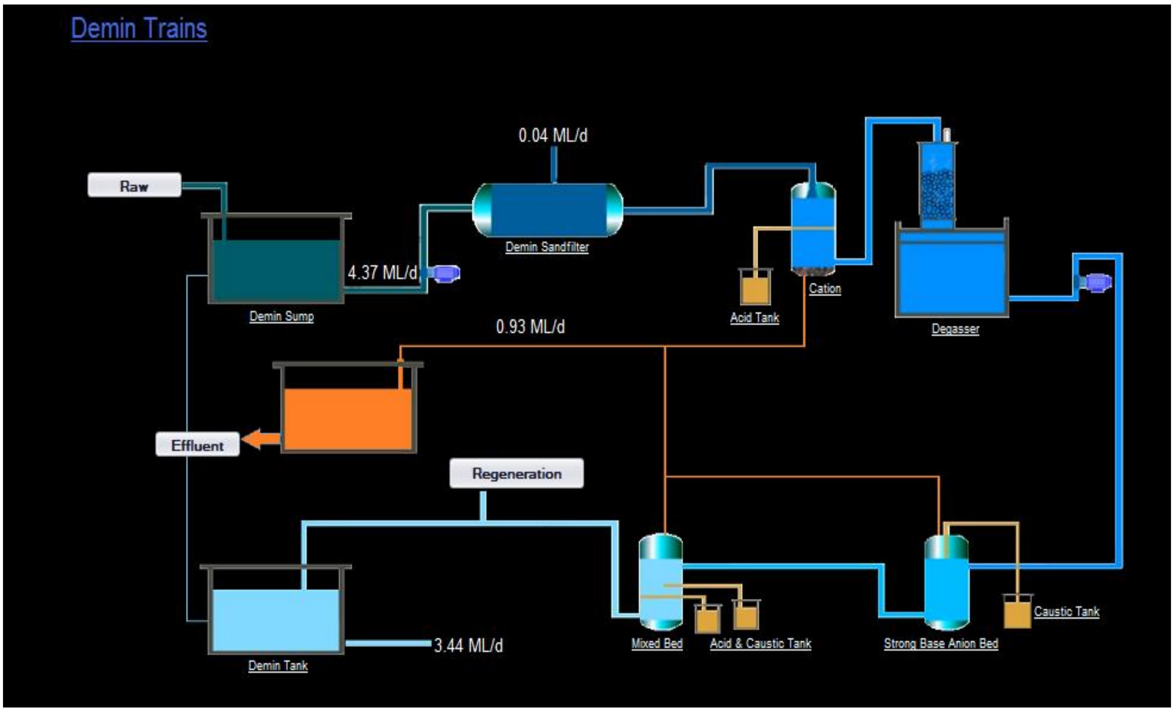
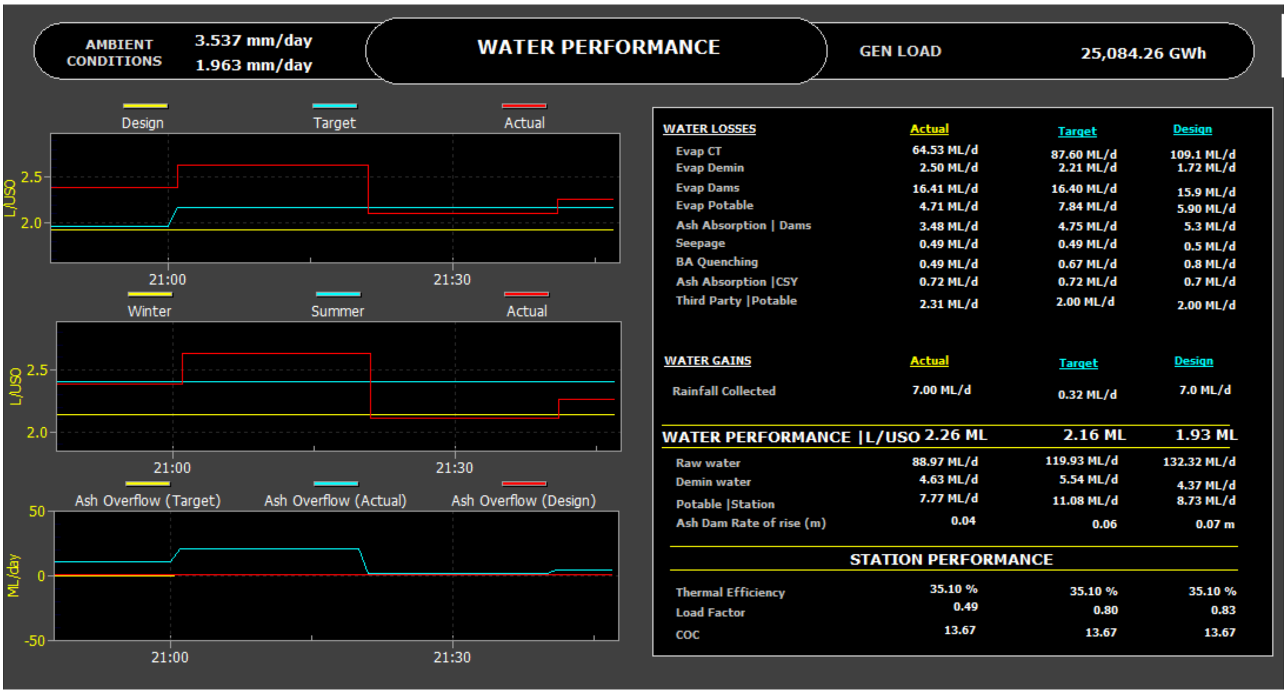


Figure 80: Demin system schematic on EtaPRO screen developer

Dashboards provide a good overview of power plant performance with key parameters displayed for deviation indication. Figure 81 illustrates the comparison between the different cases and trends depicting changes over time. An actual case water balance model was not developed in this dissertation. This can be implemented on a real time system based on the availability of data measurements and different plant configurations.



AMBIENT CONDITIONS 3.537 mm/day
1.963 mm/day

WATER PERFORMANCE

GEN LOAD 25,084.26 GWh

WATER LOSSES	Actual	Target	Design
Evap CT	64.53 ML/d	87.60 ML/d	109.1 ML/d
Evap Demin	2.50 ML/d	2.21 ML/d	1.72 ML/d
Evap Dams	16.41 ML/d	16.40 ML/d	15.9 ML/d
Evap Potable	4.71 ML/d	7.84 ML/d	5.90 ML/d
Ash Absorption | Dams	3.48 ML/d	4.75 ML/d	5.3 ML/d
Seepage	0.49 ML/d	0.49 ML/d	0.5 ML/d
BA Quenching	0.49 ML/d	0.67 ML/d	0.8 ML/d
Ash Absorption |CSY	0.72 ML/d	0.72 ML/d	0.7 ML/d
Third Party |Potable	2.31 ML/d	2.00 ML/d	2.00 ML/d
WATER GAINS	**Actual**	**Target**	**Design**
Rainfall Collected	7.00 ML/d	0.32 ML/d	7.0 ML/d
WATER PERFORMANCE |L/USO	**2.26 ML**	**2.16 ML**	**1.93 ML**
Raw water	88.97 ML/d	119.93 ML/d	132.32 ML/d
Demin water	4.63 ML/d	5.54 ML/d	4.37 ML/d
Potable |Station	7.77 ML/d	11.08 ML/d	8.73 ML/d
Ash Dam Rate of rise (m)	0.04	0.06	0.07 m
STATION PERFORMANCE			
Thermal Efficiency	35.10 %	35.10 %	35.10 %
Load Factor	0.49	0.80	0.83
COC	13.67	13.67	13.67

Figure 81: Illustrative demonstration of the water performance dashboard on EtaPRO

As a proof of concept, historic data was gathered from a selected power plant and an actual case was simulated onto the system for selected available data points. This emulates actual results as if real time data measurements exist on the system. It should be noted that one would really only need to implement an "Actual" water balance model in the case where there are no physical measurements at all the desired locations.

With the different cases developed, the user can, at any given time, account for system anomalies when comparing to the target and design values.

The raw input data used was a collection of points calculated as monthly averages in an Excel file for a period of 3 years. The associated window period was also set to a month for the various cases. The data was simulated on EtaPRO by means of rescaling the timeframe to refresh a single data point (representing a monthly mean value) every twenty minutes in Ml/day in order to develop a trend for illustration purposes. It should be noted that in order to compare the actual, target, and design case, all data should be calculated and displayed on the same window period/timescale. The design case is based on fixed values and therefore remains constant as a baseline comparison. The same applies to the summer and winter cases where only the rainfall and evaporation parameters were adjusted to generate data. Eskom requires reporting of performance data on a monthly basis as most raw input data are often captured as total monthly aggregates.

Moving averages were not implemented to smooth data for this simulation, as only total monthly volumes were available at the time of development. A moving monthly average would require at least 3 months of data storage before the moving average values are available.

Moving averages would be applied for data available at a higher resolution (hourly or daily). In the development of an actual water balance model, careful consideration should be taken to ensure that all data used for comparative purposes should be converted to the same time scale. This is possible within EtaPRO by making use of existing functionality. These functions include EPAccumulator that aggregates acquired data over time with outputs such as total, mean, or time weighted averages.

4.2 Observations from the implemented model

EtaPRO acquires current process data and calculates current performance, but to make this information truly useful it must be compared against the desired performance. The desired performance can be based either on thermal models using equipment data and test results, or be based on historical data under similar operating conditions as in the past. This provides a view on how the plant is performing against how it should be performing. Only by this comparison can changes be observed over time, especially if the changes are subtle.

The water balance framework developed on EtaPRO consists of the two Excel models used by Eskom. The first model was used to set performance targets for power plants using only inflows and outflows from the power plant. The second Excel model, referred to as the water balance model, was used to account for deviations from design for each sub-system.

However, due to the potable water not calculated at this point, and for the sake of consistency, the new approach was to make use of a water balance method to calculate the unknown values. The water balance methodology was used to develop a Mathcad model to account for the raw water consumption based on design conditions. By specifying certain performance criteria for the power plant, a target water balance model can be developed. The same method can be used to develop an actual case water balance model for comparison where limited data is available. This allows for the water balance on sub-systems to output values that can be used to more accurately predict the power plant target performance as well as have intermediate process values for comparison and trending.

The water balance model developed in Excel was based on the assumptions that there is no accumulation of water in storage systems and that the levels in water storage tanks remain constant. Thus, the model is not dynamic and is based on static conditions. This is a fair assumption for window periods greater than 30 days. Hence, all inputs are time weighted monthly averages.

5. Conclusions and Recommendations

5.1 Conclusions

Water management at Eskom coal-fired power plants is a key focus area for improvement together with advanced analytics programmes. This opened up an opportunity to explore bridging the gap of water management systems and thermal performance tools. EtaPRO Client, which is extensively used as a performance and monitoring tool, presented an ideal platform to create a water balance framework that could be standardised across power plants, and to allow for more effective real time monitoring.

The methodology described in Chapter 3 allowed for the creation of a water balance model in a systematic way on the EtaPRO Client system by means of the development of calculation templates. The Mathcad model was developed and used to ensure engineering unit consistency by means of introducing conversion factors, as well the validation of the EtaPRO calculations.

The templates used to develop the water balance model were structured such that it can be applied to various approaches in developing a water balance model with varying plant configurations. Thus, it can be concluded that once the plant configuration and water related components are identified, the methodology developed in conjunction with calculation templates may be utilised to develop water balance models on EtaPRO.

By applying the water balance method on a real time system, targets that are more accurate can be established on a monthly basis, rather than an average annual target. This can be improved further with additional data measurements on a reduced period. This is extremely valuable at a power plant where varying conditions in both power plant performance, raw water quality, coal quality, and climate conditions have a significant impact on the water consumption.

The water balance framework developed forms a foundation for setting up water balance models at various power plants. However, the availability of data may vary between power plants, implying slight changes on the sequence of equations. This tool requires continuous review and improvements, with new flow meter installations or performance test information.

The model developed in EtaPRO confirmed that calculation templates could be developed and used on EtaPRO to create water balance models that are able to replace the Excel based tools currently used in Eskom.

5.2 Assessment of current water balance models

The current Eskom Excel models were developed based on the existing plant configuration at the time of development with specific user requirements. This was not well documented and made it extremely difficult to follow the sequence of calculations or methodology used.

It was crucial to first asses the plant configurations used and its applicability to developing a water balance model and target tool. When the plant configuration and calculations were assessed in the target tool, the following were observed:

- Not all inflows and outflows were accounted for due to the lack of a pre-defined methodology in performing the overall system mass balance. This also created unnecessary assumptions.
- The ash absorption from the CSY was not included in the target tool calculation.
- The AIH and run-off coefficient values were used as constant values for all power plants, rather than calculated for each power plant based on the theory discussed in Section 2.9.2.
- The potable loss due to evaporation and supply to third party users, such as mines, were not included in the target tool.
- The areas on the ash dam change over time (annually) due to ash build-up for the ash dam wall development, and pool sizes that may change based on holding capacity of the dam. Surface areas were input as fixed values without informing the user the need to change as required.
- The target value for water consumption was set for a fixed window period of one year. This was sufficient for setting a KPI for the upcoming financial year. However, the power plant monthly performance value was captured and compared to a yearly target value. This is inconsistent especially with changing load factors, coal qualities and climatic conditions (winter and summer).
- Input requirements and changes to inputs were extremely difficult to track over time.

These shortcomings were addressed in the new approach by catering for all inflows and outflows of the system by clearly defining each system as a water flow network, as shown in Chapter 3. The NV records created also allowed the user to easily update surface areas and track changes on the system. The development of a target case in EtaPRO allows monthly targets to be established more accurately by accessing real time weather and plant data. This ensures actual and target values are compared on the same timescales.

The Eskom water balance model was developed originally for environmental reporting purposes and not monitoring and trending. Hence, no clear framework was defined on how to set up a water balance model at a power plant according to plant configuration and data requirements for monitoring and trending. The Excel model also developed the water balance using the raw water flow as the starting point and then applying a design split into sub-systems. The majority of the data inputs were based on design values, target values, or experimental tests conducted. Most of these values still remain valid in the design application. However, for a real time system it was important to understand how the system can be developed to reduce the number of assumptions made and improve accuracy.

This rigid development of the Excel model limited flexibility in customising the water balance according to specific plant and data requirements. The new methodology developed was aimed at addressing this shortcoming in the Excel model by clearly defining the system of equations required to develop an entire water network by the use of mass balance equations. It also touched on the various sources of inputs.

Using the new framework, the Demin consumption was identified as the starting point for the new model development as it is measured and readily available on the plant historian and on EtaPRO. It is important to note that by using the water balance framework, the starting point can be easily changed depending on more accurate sources of data. This was previously not possible with the Excel tool. The new framework allows the user to solve for the unknown streams by applying either the MB_IN or MB_OUT calculation.

An analysis was conducted on the systems currently available in Eskom and the data that could be readily extracted. After analysing the inputs, it was observed that key inputs could be updated in real time on EtaPRO for a target and actual water balance development. EtaPRO captures the power plant capacity and generation, load factors, thermal efficiency, coal qualities, and Demin water losses. Hence, the EtaPRO model reduces the number of manual inputs required by the user. This results in an automated water balance model.

The following inputs for an actual water balance were noted as areas of improvement based on the information available:

- A design factor was used for the backwash (node CWO016) flow calculation. If no flow meters are available to measure this node, conducting tests is recommended to update the actual correlation between the backwash flow and the clarifier flow to the sand filters.
- Similarly, the clarifier blowdown (node RAW005 and node CWO13) values should ideally be measured. However, in the absence of flow meters, logging the frequency and duration of the blowdowns can be used to verify the correlations used in the Excel model.
- Correlations in the Excel model were developed based on experimental tests conducted at specific power plants. Due to power plant design changes, this exercise should be conducted

at all power plants to verify and update data accordingly. This is required specifically for values such as clarifier solids percentage and sewage plant solids percentage.

- The Excel tool uses a correlation for calculating the cooling tower evaporation rate. This can be improved based on data available on EtaPRO (heat rejection, CW flowrates, and CW temperatures) as discussed in Section 3.5 .
- The new methodology removed the major assumption of having a 90% split of raw water to the CW system and allowed a new split to be calculated.

The Excel model currently utilised by Eskom was revised and improvements made such that a water balance model can be developed with a minimum set of data requirements. Thus, power plants with limited flow meter data can still develop water balance models and improve water management practices.

This dissertation specifically addresses the development of a water balance to understand the water distribution (where the water goes) using an online platform. This allows for improve quantification of water flows and therefore offers water saving opportunities in identifying water leaks and misuse.

5.3 Recommendations

Data reliability and availability is crucial when developing and using a water balance tools on a power plant for performance and monitoring. The water balance framework developed in EtaPRO was designed such that it can be linked to real time data points and it is therefore recommended that power plants prioritise the installation of flow meters on critical water streams to ensure accuracy of future model development and utilisation.

The critical water streams were identified as:

- CW make-up
- Raw and CW clarifier inflow
- Demin consumption
- Potable consumption (sewage plant, internal, and third party uses)
- Effluent streams (blowdown water, Demin effluent, final sewage discharge, and ash water return flows)
- Station drains
- Dust suppression
- Any recovery streams into the CW system
- CW overflows

The potable to drains factor, PTD001, remains unknown due to this not metered on any site. The measurement of potable water flows to the station drains can prove to be extremely difficult, especially as this is the result of cleaning and cooling equipment. Potable water is also an expensive water source used for cleaning. Therefore, it is recommended that power plants abstain from using potable water for cleaning and cooling of equipment unless under emergency situations. The ash water return from the ash dams can be used as an alternative water source for cleaning purposes. This will allow for the complete accounting of the potable water distribution.

With sufficient measurements available, the water balance model can be improved to include storage tank water levels and accumulation within dams. This would allow for a more accurate dynamic model, especially on Demin tanks, ash dams, and raw water reservoirs.

The ash system in itself has various factors affecting the ash dam balance at any given time. Due to the scope limitation of this research to an overall system balance, assumptions were made regarding the conditions on the ash dams. The ash dam templates can be developed further to include stage capacity curves and operational conditions affecting the management of water on the ash dam.

The focus of this dissertation was on wet-cooled coal-fired power plants with wet ashing systems and Demin production using ion exchange. Additional calculation templates can be developed as future work for systems with varying technologies.

The work completed in this dissertation creates the foundation for additional sub-system model development and integration into the overall system model. Providing further research into high water consuming processes such as cooling tower evaporation and setting up a water balance framework, allows for development of minimisation and optimization strategies. With a more informed outlook on water use at power plants, this work can be further developed into water reduction strategies as a prioritisation exercise

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Appendix A. Mathcad analytical Design base model development

A.1 Water balance calculation inputs

Power plant performance

$t := 365\text{day}$	Window Period for Design case
$W_{output} := 600\text{MW}$	Power Station Maximum Capacity Rating
$W_{aux} := 25\text{MW}$	Aux power actual
$\eta_d := 35.1\%$	Station Design Thermal Efficiency
$L_f := 0.83$	Design Load factor
$\eta_a := 35.1\%$	Actual efficiency
$n_1 := 3$	Number of Generating Units on South
$n_2 := 3$	Number of Generating Units on North
$\rho_w := 998\,\frac{\text{kg}}{\text{m}^3}$	Density of water
$w_{evap.ct} := 1.563\,\frac{\text{ML}}{\text{GW}\cdot\text{hr}}$	Cooling Tower design evaporation rates
$w_{drift} := 0.024\,\frac{\text{ML}}{\text{GW}\cdot\text{hr}}$	Windage losses from Cooling Tower
$w_{dem} := 0.05\,\frac{\text{ML}}{\text{GW}\cdot\text{hr}}$	Demin water to station
$Perc_{dem} := 50\%$	Demin water evaporated as steam

Coal quality

$CV_{coal} := 22.7\,\frac{\text{MJ}}{\text{kg}}$	Coal Caloric Value (As Recieved)
$x_{ash} := 27.2\%$	Ash Content in coal
$x_{flyash} := 75\%$	Fly Ash Content
$x_{coarseash} := 25\%$	Coarse Ash Content
$Perc_{AIH} := 60\%$	Ash Initial Hold, mositure % of wet ash
$\rho_{ash} := 900\,\frac{\text{kg}}{\text{m}^3}$	Ash density
$f_q := 0.34$	Bottom Ash Quenching factor

Raw water quality and clarifier characteristics

C_1 is for source water Komati and C_2 is for source water Vaal for where two sources exist.

$$C_1 := \begin{pmatrix} 32.3 \\ 38.8 \\ 10.3 \\ 0.017 \\ 8.3 \\ 33.6 \\ 6 \\ 45.5 \end{pmatrix} \frac{\text{mg}}{\text{L}} \qquad \begin{pmatrix} \text{Ca2} \\ \text{Mg2} \\ \text{Na} \\ \text{NH}_3 \\ \text{Cl} \\ \text{SO}_4 \\ \text{SiO} \\ \text{M}_{\text{Alk}} \end{pmatrix} := \begin{pmatrix} 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{pmatrix} \qquad C_2 := \begin{pmatrix} 124 \\ 100 \\ 34.2 \\ 0.91 \\ 21.3 \\ 231 \\ 44 \\ 130 \end{pmatrix} \frac{\text{mg}}{\text{L}}$$

Eskom Chemistry Standard Cooling Water

$$C_{limit} := \begin{pmatrix} 500 \\ 2500 \\ 500 \\ 40 \\ 400 \\ 1000 \\ 150 \\ 120 \end{pmatrix} \frac{\text{mg}}{\text{L}} \qquad \begin{pmatrix} \text{None} \\ \text{Acid} \\ \text{Lime} \end{pmatrix} := \begin{pmatrix} 0 \\ 1 \\ 2 \end{pmatrix} \qquad \text{Dosing} := \text{Lime}$$

Dosing can either be Acid, Lime or None
User has to select Dosing Option
$\text{NTU} := 1$
$\text{Turb} := 12.6\,\text{NTU}$

Clarifier Blow down inputs/assumptions

$S_{cw} := 5\%$	Solids percentage in the CW
$S_{raw} := 2\%$	Solids percentage in the raw water

Climatic conditions and dam surface areas

$E'_{pond} := 1292\frac{\text{mm}}{\text{yr}} = 3.537\frac{\text{mm}}{\text{day}}$	Pond evaporation rate averaged per annum
$E'_{ash} := 0.85\cdot E'_{pond} = 3.007\frac{\text{mm}}{\text{day}}$	Ash Phase evap rate 80% of Pond rate
$f_{pan} := 0.85$	Pan Factor
$As_{active} := 370\,\text{hectare}$	Surface area of total active ash dump
$As_{pool} := 60\,\text{hectare}$	Surface area of ash dump pools
$As_{silt} := 9.46\,\text{hectare}$	Surface area of ash water dams and silt traps
$As_{ashdam} := 440\,\text{hectare}$	Catchment surface area of the ash dam
$As_{raw} := 15.3\,\text{hectare}$	Raw water reservoir surface area
$As_{terrace} := 85.74\,\text{hectare}$	Station drainage surface area

$As_{csy} := 36\,\text{hectare}$	Coal Stock Yard surface area
$As_{sew} := 0.5\,\text{hectare}$	Sewage Plant area
$\text{Seepage} := 1\,\dfrac{\dfrac{m^3}{\text{hectare}}}{\text{day}}$	Seepage rate F Hodgson report (0.79)
$A_{s.AD} := 483\,\text{hectare}$	Ash Dam area+LLD+HLD
$A_{s.LLD.ST} := 25.2\,\text{hectare}$	Low level dama and silt trap area
$A_{s.HLD} := 2.8\,\text{hectare}$	High Level dam area
$R_{ash\_water} := 10$	Ash to water Ratio
$i_{rain} := 717\,\dfrac{mm}{yr} = 1.963\,\dfrac{mm}{day}$	Rainfall avergaed per annum

Run-off factors

Run off factor Inputs

$SAI012 := 4.34\,\text{hectare}$
$SAI013 := 0.46\,\text{hectare}$
$SAI014 := 26.4\,\text{hectare}$
$SAI015 := 3.2\,\text{hectare}$
$SAI016 := 6.89\,\text{hectare}$
$SAI017 := 51.7\,\text{hectare}$

$FAC004 := 0$
$FAC005 := 0$
$FAC006 := 1$
$FAC007 := 1$
$FAC008 := 0.7..$
$FAC009 := 0.6$

$f_{r.ashdam} := 0.4$	Pg 57 Drainage manual Runoff factor for ash dam
$f_{r.terrace} := 0.726$	Zled study Runoff factor for Station terrace

Dust suppression

Cooling water from the hot duct on the South is tapped off for dust supression at the Coal stock yard and roads to ash dam. This value has been averaged

$$v'_{ds} := 1.2\,\frac{ML}{day}$$

Potable system

$Perc_{p\_dem} := 10\%$	Design estimation for raw to potable and demin
$Perc_{bw} := 1\%$	Back wash flow from potable and demin sandfilter

Demin plant

$v_{dem.cap} := 7080\,m^3$	Single Demin train run length before regen is required
$v_{dem.regen} := 1400\,m^3$	Effluent produced per demin regen
$v_{cpp.regen} := 250\,m^3$	Effluent produced per CPP regen
$n_{cpp.run} := \dfrac{1}{day}$	Number of CPP regens per day (0.1 to 3)

Sewage plant

$V_{sew.a} := 105.8\,ML$ Sewage to Ash dam recorded on plant 2017 avg

Assuming that a percentage of potable water enters the sewage plant. one can calculate the theoritical flows

$Perc_{p\_sew} := 10\%$ $S_{sew} := 5\%$

A.2 Power plant water consumers

Figure 24 was used as the overall plant configuration for the calculations in this section.

Calculate the power station Unit Sent Out as the basis for subsequent calculations

$W_{net} := \left[\left(W_{output} - W_{aux}\right)\cdot\left(n_1 + n_2\right)\right]\cdot t\cdot L_f = 25084.26\cdot GW\cdot hr$ Unit Sent Out

Calculate Coal Burn Rate based on Coal Quality, target efficiency and load factor

$$m'_{coal.d} := \frac{\left[W_{output}\cdot\left(n_1 + n_2\right)\right]\cdot L_f}{CV_{coal}\cdot\eta_d} = 32401.22\frac{tonne}{day}$$

$$Q'_{coal} := \frac{m'_{coal.d}\cdot t}{W_{net}} = 471\cdot\frac{tonne}{GW\cdot hr}$$ calculated coal burned

Calculate the mass and volume of fly and coarse ash produced from the boiler after combustion.

$$m_{ash} := W_{net}\cdot Q'_{coal}\cdot x_{ash} = 3216793.11\,tonne$$

$$v_{ash} := \frac{m_{ash}}{\rho_{ash}} = 3574.21\,ML$$

$$m_{flyash} := x_{flyash}\cdot m_{ash} = 2412594.84\,tonne$$

$$m_{coarseash} := x_{coarseash}\cdot m_{ash} = 804198.28\,tonne$$

Calculate the volume of water lost due to ash absorption on the ash dam

$$v_{flyash\_w} := \frac{m_{flyash}\cdot Perc_{AIH}}{\rho_w} = 1450.46\cdot ML$$ Fly Ash

$$v_{coarseash\_w} := \frac{m_{coarseash}\cdot Perc_{AIH}}{\rho_w} = 483\cdot ML$$ Coarse Ash

Total water due to ash absorption

$$v_{t.ashwater} := v_{flyash\_w} + v_{coarseash\_w} = 1933.94\cdot ML$$

Cooling water make requirement

The design cooling tower evaporation rate was used for the design case calculation of evaporation loss.

Calculate cooling tower evaporation losses based on the design evaporation rate

$v_{evap.ct} := W_{net} \cdot w_{evap.ct} = 39.207 \times 10^{3} \cdot ML$ From design

$v_{drift} := W_{net} \cdot w_{drift} = 602.022ML$ CT drift and windage losses

$Cf_{evap} := \left(\eta_{d} - \eta_{a}\right) \cdot 0.04 W_{net} \cdot \frac{L}{kW \cdot hr} = 0 \cdot ML$ Correction factor for efficiency

Cooling tower losses are directly related to the efficiency of the power plant and therefore correlations can be used to determine the cooling tower evaporation at various thermal efficiencies

$v_{t.evap.ct} := \left(v_{evap.ct} + v_{drift}\right) + Cf_{evap} = 39809ML$ Design CT losses incl CF

Rainfall collection from dams and station terrace

The rainfall on all dams was calculated in one section and will be fed into each system balance as required.

$v_{terrace} := f_{r.terrace} \cdot i_{rain} \cdot As_{terrace} \cdot t = 446 \cdot ML$ Rain on station terrace

$v_{ashdam} := f_{r.ashdam} \cdot i_{rain} \cdot As_{ashdam} \cdot t = 1261.08 \cdot ML$ Rain on Ash Dam catchment

$v_{csy} := f_{r.ashdam} \cdot i_{rain} \cdot As_{csy} \cdot t = 103.18 \cdot ML$ Rain on CSY

$v_{pool} := i_{rain} \cdot As_{pool} \cdot t = 430 \cdot ML$ Rain on Ash dam pool

$v_{HLD} := i_{rain} \cdot A_{s.HLD} \cdot t = 20.063 \cdot ML$ Rain on HLD

$v_{LLD} := i_{rain} \cdot A_{s.LLD.ST} \cdot t = 180.564 \cdot ML$ Rain on LLD

$v_{sew} := i_{rain} \cdot As_{sew} \cdot t = 3.583 \cdot ML$ Rain on Sewage pond

$v_{rawdam} := i_{rain} \cdot As_{raw} \cdot t = 109.628 \cdot ML$ Rain on Raw water resovior

Total rain water collected on all open dams

$$v_{t.rain} := v_{terrace} + v_{pool} + v_{ashdam} + v_{HLD} + v_{LLD} \cdots + \left(v_{sew} + v_{rawdam} + v_{csy}\right) = 2554.03 \cdot ML$$

Evaporation losses from dams

The evaporation loss on all dams was calculated in one section and will be fed into each system balance as required.

$E_{pool} := As_{pool} \cdot E'_{pond} \cdot t = 775 \cdot ML$ Evap from ash dam pool

$E_{active} := As_{active} \cdot E'_{ash} \cdot t = 4061 \cdot ML$ Evap form Active Ash Disposal Site

$E_{LLD} := A_{s.LLD.ST} \cdot E'_{pond} \cdot t = 325.37 \cdot ML$ Evap from LLD & silt traps

$E_{HLD} := A_{s.HLD} \cdot E'_{pond} \cdot t = 36.15 \cdot ML$ Evap from HLD

Total water evaporated from open ash dams

$E_{t.ashdam} := E_{pool} + E_{active} + E_{LLD} + E_{HLD} = 5196.85 \cdot ML$

Evaporation from clean water dams

$E_{raw} := As_{raw} \cdot E'_{pond} \cdot t = 197.54 \cdot ML$ Evap from Raw water dam

$E_{csy} := As_{csy} \cdot E'_{ash} \cdot t = 395.09 \cdot ML$ Evap from coal stock yard

$E_{sew} := As_{sew} \cdot E'_{pond} \cdot t = 6.46 \cdot ML$ Evap from sewage

Evaporation due to bottom ash quenching and Demin losses

Evaporation during bottom ash quenching

$$E_q := \frac{m_{coarseash} \cdot f_q}{\rho_w} = 273.98\,ML$$

Demin Evaporation

$v_{dem} := w_{dem} \cdot W_{net} \cdot Perc_{dem} = 657.21\,ML$ Demin evap as steam

$v_{dem.sd} := w_{dem} \cdot W_{net} \cdot \left(1 - Perc_{dem}\right) = 597.01\,ML$ Demin to station drains

Total water lost during evaporation from all areas (Ash, raw and ponds)

$$E_t := \left(E_{t.ashdam} + E_{raw} + E_q + E_{csy} + E_{sew}\right) = 6.07 \times 10^3 \cdot ML$$

$$E_{t.corr} := f_{pan} \cdot E_t + v_{dem} = 5.817 \times 10^3 \cdot ML$$

Seepage losses and Coal Stock Yard ash absorption

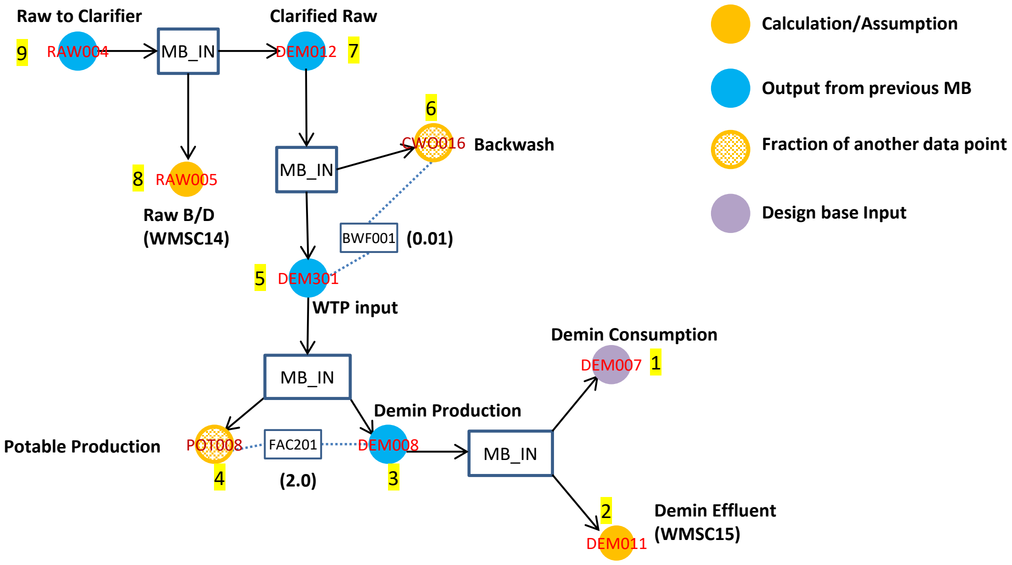
$v_{seepage} := A_{s.AD} \cdot Seepage \cdot t = 177.025\,ML$ Seepage from ash dams

$v_{csy\_abs} := Perc_{AIH} \cdot t \cdot v'_{ds} = 262.8\,ML$ Ash Absorption on CSY

A.3 Potable and Demin consumption calculation

The mass balance methodology developed in Chapter 3 was used in the sub-system mass balance development.

Demin plant schematic



Demin Plant Mass Balance 1

Mass balance calculation, inflow result: $MB\_IN(IN, OUT) := \sum OUT - \sum IN$

Mass balance calculation, outflow result: $MB\_OUT(IN, OUT) := \sum IN - \sum OUT$

Calculating known nodes

$v'_{dem.st} := \frac{w_{dem} \cdot W_{net}}{t} = 3.44 \cdot \frac{ML}{day}$ Demin flowrate to station design

$v'_{eff.dem} := \frac{v'_{dem.st}}{v_{dem.cap}} \cdot v_{dem.regen} = 0.68 \cdot \frac{ML}{day}$ Demin water used for demin regen

$v'_{eff.cpp} := v_{cpp.regen} \cdot n_{cpp.run} = 0.25 \cdot \frac{ML}{day}$ CPP regen water usage

$v'_{t.eff} := v'_{eff.cpp} + v'_{eff.dem} = 0.93 \cdot \frac{ML}{day}$ Total effluent water from WTP

Performing a water balance over the demin plant, the total water input to the demin plant could be calculated

$v'_{t.dem} := v'_{t.eff} + v'_{dem.st} = 4.37 \cdot \frac{ML}{day}$ Design Demin water at 33%

Mass balance calculation, inflow result:

$DEM008 := MB\_IN\left[(0), \begin{pmatrix} v'_{dem.st} \\ v'_{t.eff} \end{pmatrix}\right] = 4.366 \cdot \frac{ML}{day}$ Inflow Point 3

$DEM007 := v'_{dem.st}$ Outflow Point 1

$DEM011 := v'_{t.eff}$ Outflow Point 2

Potable mass balance 2

The potable flow input is calculated using the assumption of 1/3 of the water is used for demin and 2/3 is used for potable production.

$f_1 := 2$ Factor 1

$v'_{t.p} := v'_{t.dem} \cdot f_1 = 8.73 \cdot \frac{ML}{day}$ Outflow Point 4 Potable Consumption

Mass Balance for Clarifierd water 3

Mass balance calculation, inflow result:

$v'_{pot\_dem} := MB\_IN\left[(0), \begin{pmatrix} v'_{t.p} \\ v'_{t.dem} \end{pmatrix}\right] = 13.097 \cdot \frac{ML}{day}$ Inflow Point 5

$DEM301 := v'_{pot\_dem}$

$POT008 := v'_{t.p}$

Mass Balance for Clarifier Outflow 4

$v'_{bw} := Perc_{bw} \cdot v'_{pot\_dem} = 0.131 \cdot \frac{ML}{day}$ B/W flow out of potable and demin sandfilter

Mass balance calculation, inflow result:

$$v'_{cl.out} := MB\_IN\left[(0), \begin{pmatrix} v'_{bw} \\ v'_{pot\_dem} \end{pmatrix}\right] = 13.228 \cdot \frac{ML}{day}$$

$CWO016 := v'_{bw}$ Outflow Point 6

$DEM012 := v'_{cl.out}$ Inflow Point 7 to WTP

Mass Balance for Clarifier inflow 5

$$f2 := \frac{Turb \cdot \left(\frac{1}{3} \cdot \frac{mg}{L}\right)}{S_{raw} \cdot \rho_w} = 2.104 \times 10^{-4}$$ Clarifier factor

The blowndown water from the clarifier can now be calculated

$$v'_{BD.raw} := \frac{f2 \cdot v'_{cl.out}}{1 - f2} = 2.78 \times 10^{-3} \cdot \frac{ML}{day}$$

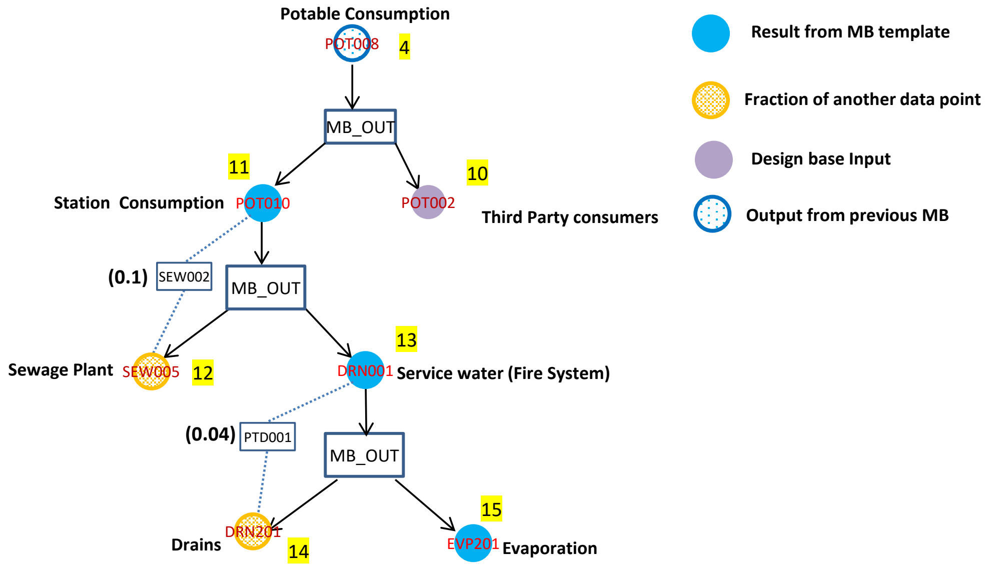
Clarifier inflow calculation result:

$$v'_{cl.in} := MB\_IN\left[(0), \begin{pmatrix} v'_{BD.raw} \\ v'_{cl.out} \end{pmatrix}\right] = 13.231 \cdot \frac{ML}{day}$$

$RAW005 := v'_{BD.raw}$

$RAW004 := v'_{cl.in}$

Potable system schematic



Potable to Station Mass Balance 6

The potable produced sent to the station is the design potable minus the third party uses such as mines

$v'_{p\_mine} := 2\,\frac{ML}{day}$

Outflow Point 10 Potable to mine

$v'_{p\_st} := v'_{t.p} - v'_{p\_mine} = 6.73\cdot\frac{ML}{day}$

Potable to station outflow result:

$POT010 := MB\_OUT\left[\left(v'_{t.p}\right),\left(v'_{p\_mine}\right)\right] = 6.731\cdot\frac{ML}{day}$

Outflow Point 11

$POT002 := v'_{p\_mine}$

Sewage Mass Balance 7

$Perc_{p\_sew} := 10\%$

Percentage of Potable to sewage

$v'_{sew.st} := Perc_{p\_sew}\cdot v'_{p\_st} = 0.67\cdot\frac{ML}{day}$

Outflow Point 12

$v'_{p.FW} := v'_{p\_st} - v'_{sew.st} = 6.06\cdot\frac{ML}{day}$

Design Potable to fire station

Potable outflow used as fire water/services result:

$DRN001 := MB\_OUT\left[\left(v'_{p\_st}\right),\left(v'_{sew.st}\right)\right] = 6.058\cdot\frac{ML}{day}$

Outflow Point 13

$SEW005 := v'_{sew.st}$

Fire Water Mass Balance 8

$Perc_{p\_drains} := 4\%$ Percentage of Service water to drains

$v'_{p\_drains} := v'_{p.FW} \cdot Perc_{p\_drains} = 0.242 \cdot \frac{ML}{day}$ Outflow Point 14 Potable to drains

$v'_{p\_evap} := v'_{p.FW} - v'_{p\_drains} = 5.82 \cdot \frac{ML}{day}$ Outflow Point 15 Potable evaporated

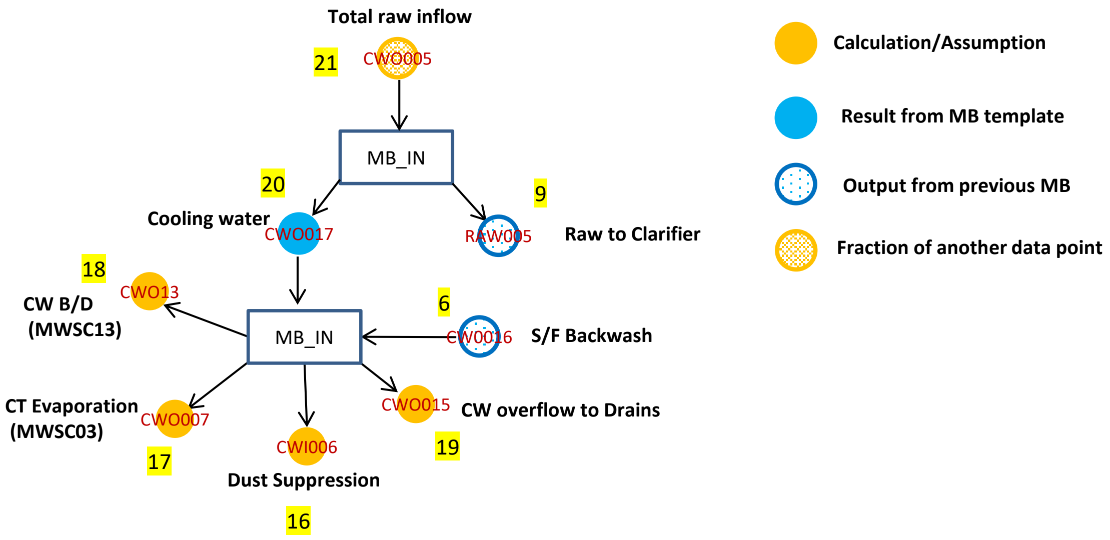
Potable evaporated as an outflow result:

$EVP201 := MB\_OUT\left[\left(v'_{p.FW}\right), \left(v'_{p\_drains}\right)\right] = 5.816 \cdot \frac{ML}{day}$

$DRN201 := v'_{p\_drains}$

A.4 Raw and cooling water calculation

Refer to Figure 51 for schematic used for calculation development



Cycles of Concentration (COC) calculation

$i := 0..6$

$$n_{CC.1_i} := \frac{C_{limit_i}}{C_{1_i}} \qquad n_{CC.2_i} := \frac{C_{limit_i}}{C_{2_i}}$$

$$n_{CC.1_{SO_4}} := \left[\frac{0.9\cdot\left(C_{limit_{SO_4}}\right)}{C_{1_{SO_4}} + \left[C_{1_{SO_4}}\cdot(0.98)\cdot\left(\frac{96}{98}\right)\right]}\right] \qquad n_{CC.2_{SO_4}} := \left[\frac{0.9\cdot\left(C_{limit_{SO_4}}\right)}{C_{2_{SO_4}} + \left[C_{2_{SO_4}}\cdot(0.98)\cdot\left(\frac{96}{98}\right)\right]}\right]$$

$$n_{CC.1_{Mg2}} := \sqrt{\frac{C_{limit_{Mg2}}\cdot C_{limit_{SiO}}}{C_{1_{Mg2}}\cdot C_{1_{SiO}}}} \qquad n_{CC.2_{Mg2}} := \sqrt{\frac{C_{limit_{Mg2}}\cdot C_{limit_{SiO}}}{C_{2_{Mg2}}\cdot C_{2_{SiO}}}}$$

$$n_{CC.1LimeDose} := \mathrm{submatrix}\left(n_{CC.1}, 1, 6, 0, 0\right) \qquad n_{CC.2LimeDose} := \mathrm{submatrix}\left(n_{CC.2}, 1, 6, 0, 0\right)$$

Two raw water sources were analysed as most stations have multiple raw water sources.

$$n_{CC.1f} := \left|\begin{array}{l} COC_{1f} \leftarrow \min\left(n_{CC.1}\right) \text{ if } Dosing = None \vee Dosing = Acid \\ COC_{2f} \leftarrow \min\left(n_{CC.1LimeDose}\right) \text{ if } Dosing = Lime \end{array}\right.$$

$$n_{CC.2f} := \left|\begin{array}{l} COC_{1f} \leftarrow \min\left(n_{CC.2}\right) \text{ if } Dosing = None \vee Dosing = Acid \\ COC_{1f} \leftarrow \min\left(n_{CC.2LimeDose}\right) \text{ if } Dosing = Lime \end{array}\right.$$

$$\boxed{n_{CC.1f} = 14} \qquad \boxed{n_{CC.2f} = 2}$$

$$v'_{t.evap.ct} := \frac{v_{t.evap.ct}}{t} = 109.065\cdot\frac{ML}{day}$$

Inclusive of drift and windage losses

$CWO007 := v'_{t.evap.ct}$

Point 17

Blowdown water calculation:
Assume evaporation is equal on both north and south side

$$v'_{evap.1} := \frac{v'_{t.evap.ct}}{2} = 54.53\cdot\frac{ML}{day}$$

$$v'_{evap.2} := \frac{v'_{t.evap.ct}}{2} = 54.53\cdot\frac{ML}{day}$$

Calculate the blowdown from the COC

$$v'_{BD.1} := \frac{v'_{evap.1}}{n_{CC.1f} - 1} = 4.31\cdot\frac{ML}{day} \qquad v'_{BD.2} := \frac{v'_{evap.1}}{n_{CC.1f} - 1} = 4.31\cdot\frac{ML}{day}$$

Total Blow down water from the South and North systems

$v'_{BD.cw} := v'_{BD.1} + v'_{BD.2} = 8.61 \cdot \frac{ML}{day}$

$v'_{cw\_drains} := 0 \frac{ML}{day}$ Assumed 0 ML/day for design

$CWO013 := v'_{BD.cw}$ Point 18

$CWO006 := v'_{ds}$ Point 16

$CWO015 := v'_{cw\_drains}$ Point 19

Overall CW balance to calculate for the CW requirement

$$v'_{cw} := MB\_IN\left[\left(v'_{bw}\right), \begin{pmatrix} v'_{t.evap.ct} \\ v'_{BD.cw} \\ v'_{ds} \\ v'_{cw\_drains} \end{pmatrix}\right] = 118.74 \cdot \frac{ML}{day}$$

Point 20

$CWO17 := v'_{cw}$

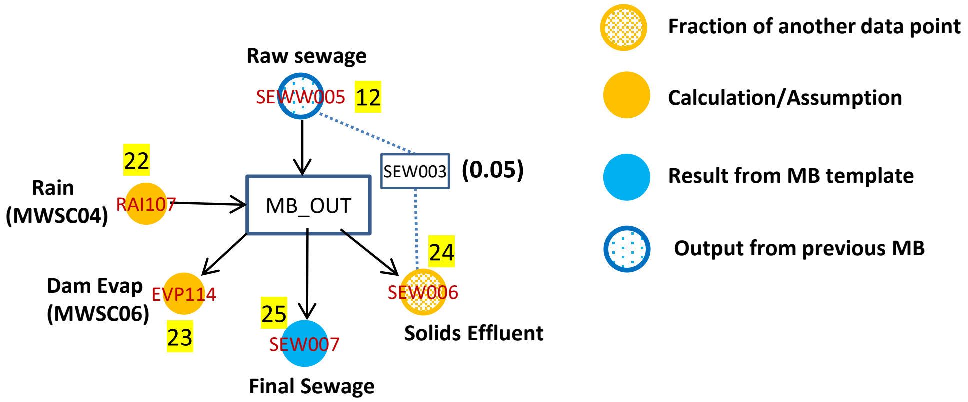
Mass Balance Calculation to calculate the total raw water supply

$$v'_{raw} := MB\_IN\left[(0), \begin{pmatrix} v'_{cw} \\ v'_{cl.in} \end{pmatrix}\right] = 131.98 \cdot \frac{ML}{day}$$

Point 21

$CWO005 := v'_{raw}$

A.5 Sewage plant final effluent



$f_{sew} := 5\%$ Percentage of solids in sewage waste

$$v'_{r.sew} := \frac{v_{sew}}{t} = 9.815 \times 10^{-3} \cdot \frac{ML}{day}$$

Rainfall calculated in Section A.2

$RAI107 := v'_{r.sew}$ Point 22

$$v'_{E.sew} := \frac{E_{sew} \cdot f_{pan}}{t} = 0.015 \cdot \frac{ML}{day}$$

Evaporation calculated in Section A.2

$EVP114 := v'_{E.sew}$ Point 23

Calculat water lost with solids from sewage maturation pond

$$v'_{sew.solids} := f_{sew} \cdot v'_{sew.st} = 0.03 \cdot \frac{ML}{day}$$

$SEW006 := v'_{sew.solids}$ Point 24

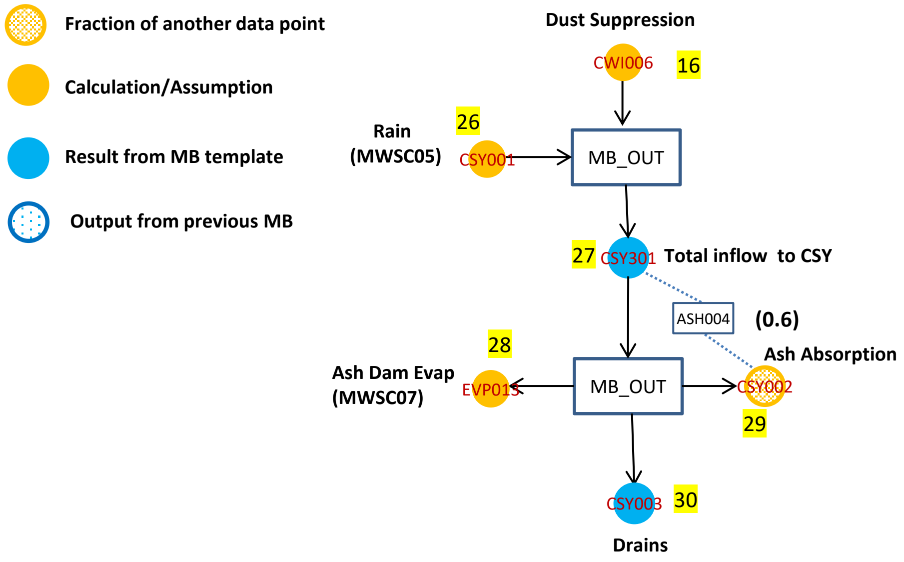
Treated sewage discharged to High Level Ash dam based on Target potable

$$v'_{sew} := MB\_OUT\left[\begin{pmatrix} v'_{sew.st} \\ v'_{r.sew} \end{pmatrix}, \begin{pmatrix} v'_{E.sew} \\ v'_{sew.solids} \end{pmatrix}\right] = 0.63 \cdot \frac{ML}{day}$$

$SEW007 := v'_{sew}$ Point 25

A.6 Coal Stock Yard calculation

Refer to Figure 53 for schematic used for calculations



$v'_{rain.csy} := As_{csy} \cdot i_{rain} = 0.707 \cdot \frac{ML}{day}$ Point 26 Rain on CSY

Mass balance outflow calc:

$v'_{csy.in} := MB\_OUT\left[\begin{pmatrix} v'_{rain.csy} \\ v'_{ds} \end{pmatrix}, (0)\right] = 1.91 \cdot \frac{ML}{day}$ Point 27

$CSY301 := v'_{csy.in}$

$v'_{E.csy} := \frac{E_{csy}}{t} \cdot f_{pan} = 0.92 \cdot \frac{ML}{day}$ Point 28

$EVP113 := v'_{E.csy}$

$v'_{csy.abs} := v'_{csy.in} \cdot Perc_{AIH} = 1.144 \cdot \frac{ML}{day}$ Point 29 Absorption on coal

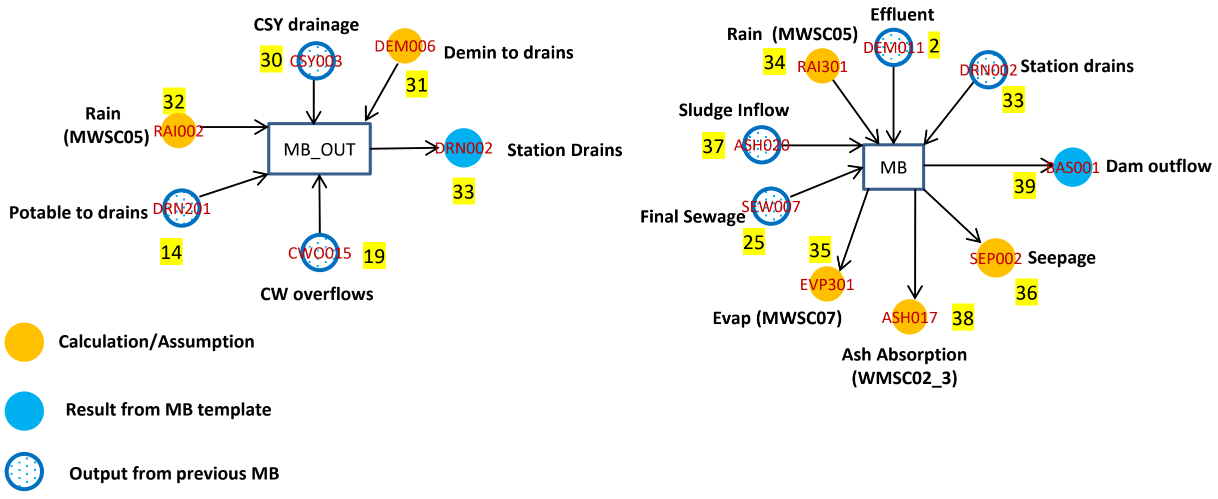
Water released to drains from CSY:

$v'_{csy.drains} := MB\_OUT\left[\left(v'_{csy.in}\right), \begin{pmatrix} v'_{csy.abs} \\ v'_{E.csy} \end{pmatrix}\right] = -0.16 \cdot \frac{ML}{day}$

$CSY003 := v'_{csy.drains}$

A.7 Drainage and Ash dam system calculation

The Calculation of total water to the power station drainage system is as per Figure 54.



$$v'_{dem.sd} := \frac{v_{dem.sd}}{t}$$

Point 31

$$v'_{terrace} := \frac{v_{terrace}}{t}$$

Point 32

$$v'_{drains.in} := \mathrm{MB\_OUT}\left[\begin{pmatrix} v'_{dem.sd} \\ v'_{terrace} \\ v'_{csy.drains} \\ v'_{cw\_drains} \\ v'_{p\_drains} \end{pmatrix},(0)\right] = 3.03\,\frac{ML}{day}$$

Point 33

$$\mathrm{DRN002} := v'_{drains.in}$$

The Ash system balance as a MB_OUT calculation.

Total blown down water collected in the sludge sump

$$v'_{t.BD} := \left(v'_{BD.cw} + v'_{BD.raw}\right) = 8.61\cdot\frac{ML}{day}$$

Point 37

$$\mathrm{ASH020} := v'_{t.BD}$$

Total rainfall on Ash dams

$$v'_{r.ash} := \frac{\left(v_{pool} + v_{ashdam} + v_{HLD} + v_{LLD}\right)}{t}$$

Point 34

$$\mathrm{RAI301} := v'_{r.ash}$$

Total evaporation loss on Ash system

$$v'_{E.ash} := \frac{\left(E_{t.ashdam}\cdot f_{pan} + E_{q}\right)}{t}$$

Point 35

$$\mathrm{EVP301} := v'_{E.ash}$$

$$v'_{seepage} := \frac{v_{seepage}}{t}$$

Point 36

$$\mathrm{SEP002} := v'_{seepage}$$

$$v'_{t.ashwater} := \frac{v_{t.ashwater}}{t}$$

Point 38

$$\mathrm{ASH017} := v'_{t.ashwater}$$

Overall Ash System Mass balance outflow calculation:

$$v'_{ash.mb} := \mathrm{MB\_OUT}\left[\begin{pmatrix} v'_{t.BD} \\ v'_{r.ash} \\ v'_{sew} \\ v'_{t.eff} \\ v'_{drains.in} \end{pmatrix},\begin{pmatrix} v'_{E.ash} \\ v'_{seepage} \\ v'_{t.ashwater} \end{pmatrix}\right] = -0.252\,\frac{ML}{day}$$

$$\mathrm{BAS001} := v'_{ash.mb}$$

Point 39

A.8 Design water performance calculation

Refer to Figure 26 for the parameters used to calculate the design water consumption from an overall system balance.

Total potable water lost from the system is thus all the third party users and evaporation losses

$$v'_{p\_loss} := v'_{p\_evap} + v'_{p\_mine} = 7.82 \cdot \frac{ML}{day}$$

$$v_{p\_loss} := v'_{p\_loss} \cdot t = 2.853 \times 10^{3} \cdot ML$$

Total raw water demand using an overall balance of the power station

$$v_{raw.d} := v_{t.evap.ct} + v_{t.ashwater} + E_{t.corr} \cdots + \left(v_{seepage} - v_{t.rain} + v_{p\_loss} + v_{csy\_abs}\right) = 4.827 \times 10^{4} \cdot ML$$

Total raw water demand using the raw water calculated using the mass balances over the sub-systems.

$$v_{raw.i} := v'_{raw} \cdot t + \left(v_{rawdam} - E_{raw} \cdot f_{pan}\right) = 4.81 \times 10^{4} \cdot ML$$

Target Water Performance Parameter

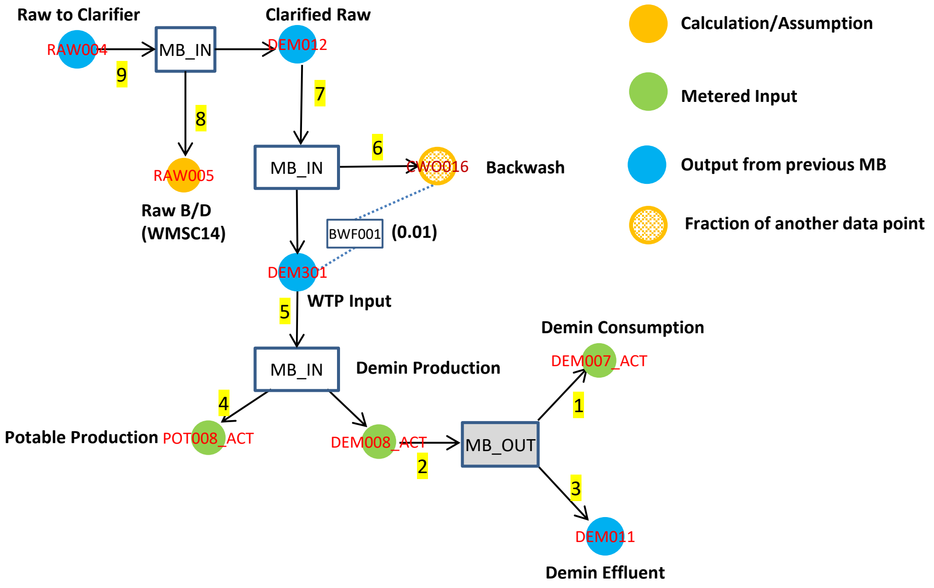
$$I_d := \frac{v_{raw.d}}{W_{net}} = 1.92 \cdot \frac{ML}{GW \cdot hr}$$

$$I_i := \frac{v_{raw.i}}{W_{net}} = 1.92 \cdot \frac{ML}{GW \cdot hr}$$

A.10 Mathcad model for Actual case on potable and Demin system

Demin plant

The actual case was developed using the same inputs as the design case in Appendix A.3.



Calculating known nodes

$v'_{dem.st} := \frac{w_{dem} \cdot W_{net}}{t} = 3.44 \cdot \frac{ML}{day}$ Point 1Demin Make-up Flow meter reading required

$v'_{t.dem} := 6 \, \frac{ML}{day}$ Point 2 Demin Train outlet Flow meter reading

Mass balance calculation for WTP Effluent, outflow result:

$DEM011 := MB\_OUT\left[\left(v'_{t.dem}\right), \left(v'_{dem.st}\right)\right] = 2.564 \cdot \frac{ML}{day}$ Outflow Point 3

$DEM007 := v'_{dem.st}$ Outflow Point 1

$DEM008 := v'_{t.dem}$ Outflow Point 2

Potable mass balance 2

$v'_{t.p} := 8\,\frac{ML}{day}$ Potable Production Flow meter

Mass Balance for Clarifierd water 3

Mass balance calculation, inflow result:

$v'_{pot\_dem} := MB\_IN\left[(0),\begin{pmatrix} v'_{t.p} \\ v'_{t.dem} \end{pmatrix}\right] = 14\cdot\frac{ML}{day}$ Point 5

$DEM301 := v'_{pot\_dem}$

$POT008 := v'_{t.p}$ Point 4

Mass Balance for Clarifier Outflow 4

$v'_{bw} := Perc_{bw}\cdot v'_{pot\_dem} = 0.14\cdot\frac{ML}{day}$ B/W flow out of potable and demin sandfilter

Mass balance calculation, inflow result:

$v'_{cl.out} := MB\_IN\left[(0),\begin{pmatrix} v'_{bw} \\ v'_{pot\_dem} \end{pmatrix}\right] = 14.14\cdot\frac{ML}{day}$

$CWO016 := v'_{bw}$ Outflow Point 6

$DEM012 := v'_{cl.out}$ Inflow Point 7 to WTP

Mass Balance for Clarifier inflow 5

$f2 := \frac{Turb\cdot\left(\frac{1}{3}\cdot\frac{mg}{L}\right)}{S_{raw}\cdot\rho_w} = 2.104\times 10^{-4}$ Clarifier factor

The blowndown water from the clarifier can now be calculated

$$v'_{BD.raw} := \frac{f2\cdot v'_{cl.out}}{1-f2} = 2.98\times 10^{-3}\cdot\frac{ML}{day}$$

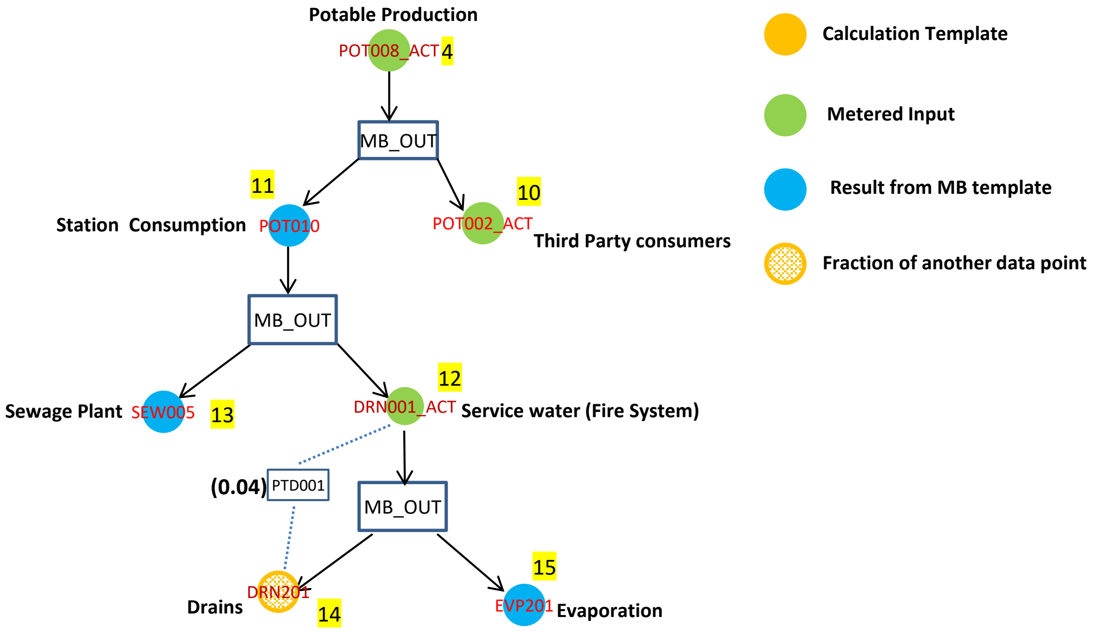
Clarifier inflow calculation result:

$$v'_{cl.in} := MB\_IN\left[(0),\begin{pmatrix} v'_{BD.raw} \\ v'_{cl.out} \end{pmatrix}\right] = 14.143\cdot\frac{ML}{day}$$

$RAW005 := v'_{BD.raw}$

$RAW004 := v'_{cl.in}$

Potable plant



Potable to Station Mass Balance 6

The potable produced sent to the station is the design potable minus the third party uses such as mines

$v'_{p\_mine} := 2 \frac{ML}{day}$ Potable to mine metered

$POT002 := v'_{p\_mine}$ Point 10

Potable to station outflow result:

$v'_{p\_st} := MB\_OUT\left[\left(v'_{t.p}\right),\left(v'_{p\_mine}\right)\right] = 6 \cdot \frac{ML}{day}$

$POT010 := v'_{p\_st}$ Point 11

Sewage Mass Balance 7

$v'_{p.FW} := 4 \frac{ML}{day}$ Outflow Point 12 Actual Potable to fire station

Potable outflow used as raw sewage result:

$SEW005 := MB\_OUT\left[\left(v'_{p\_st}\right),\left(v'_{p.FW}\right)\right] = 2 \cdot \frac{ML}{day}$ Outflow Point 13

$DRN001 := v'_{p.FW}$

Fire Water Mass Balance 8

$\mathrm{Perc}_{p\_drains} := 4\%$ Percentage of Service water to drains

$v'_{p\_drains} := v'_{p.FW} \cdot \mathrm{Perc}_{p\_drains} = 0.16 \cdot \frac{ML}{day}$ Outflow Point 14 Potable to drains

$v'_{p\_evap} := v'_{p.FW} - v'_{p\_drains} = 3.84 \cdot \frac{ML}{day}$ Outflow Point 15 Potable evaporated

Potable evaporated as an outflow result:

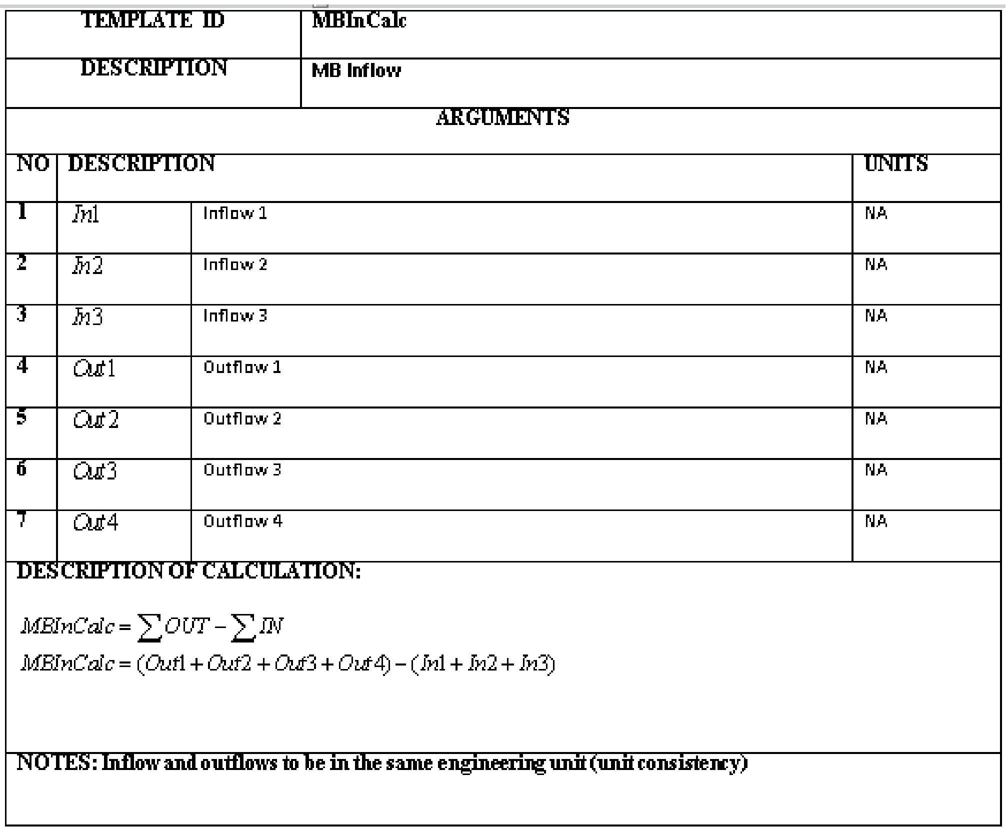
$\mathrm{EVP201} := \mathrm{MB\_OUT}\left[\left(v'_{p.FW}\right), \left(v'_{p\_drains}\right)\right] = 3.84 \cdot \frac{ML}{day}$

$\mathrm{DRN201} := v'_{p\_drains}$

Appendix B. EtaPRO Calculation Templates

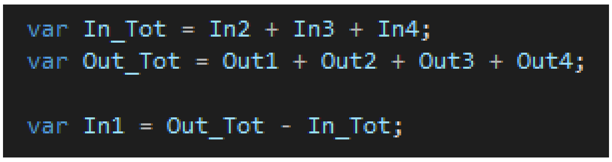
1. MBInCalc: MB Inflow

Calculation Template:



TEMPLATE ID	**MBInCalc**		
DESCRIPTION	**MB Inflow**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$In1$	Inflow 1	NA
2	$In2$	Inflow 2	NA
3	$In3$	Inflow 3	NA
4	$Out1$	Outflow 1	NA
5	$Out2$	Outflow 2	NA
6	$Out3$	Outflow 3	NA
7	$Out4$	Outflow 4	NA
DESCRIPTION OF CALCULATION: $MBInCalc = \sum OUT - \sum IN$ $MBInCalc = (Out1 + Out2 + Out3 + Out4) - (In1 + In2 + In3)$			
NOTES: Inflow and outflows to be in the same engineering unit (unit consistency)			

C# Code:

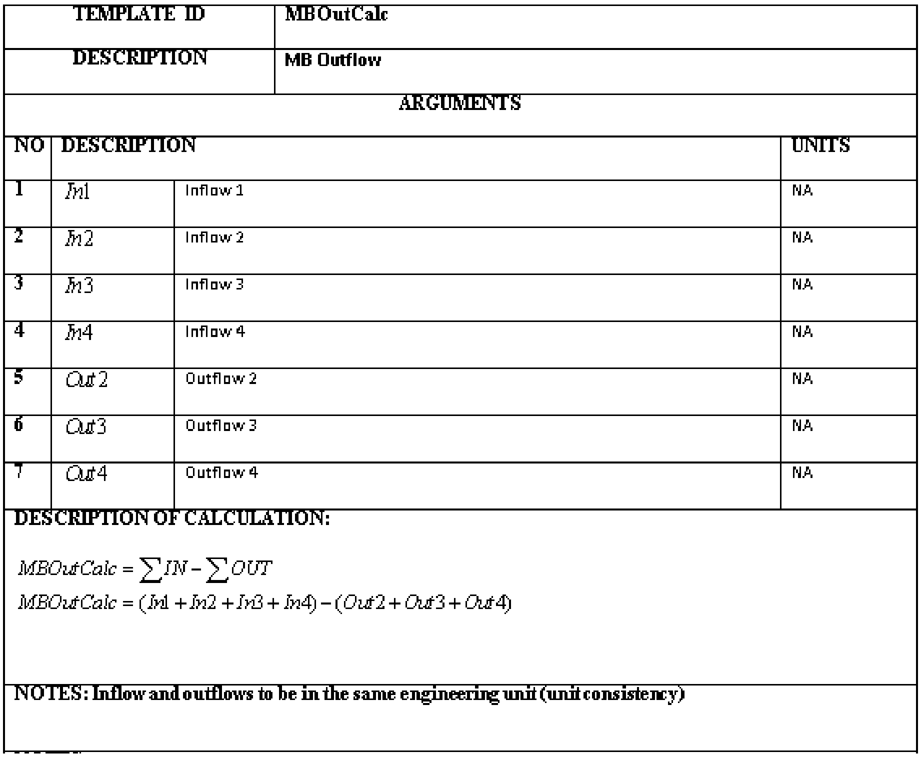


```
var In_Tot = In2 + In3 + In4;
var Out_Tot = Out1 + Out2 + Out3 + Out4;

var In1 = Out_Tot - In_Tot;
```

2. MBOutCalc: MB Outflow

Calculation Template:



TEMPLATE ID	**MBOutCalc**		
DESCRIPTION	**MB Outflow**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$In1$	Inflow 1	NA
2	$In2$	Inflow 2	NA
3	$In3$	Inflow 3	NA
4	$In4$	Inflow 4	NA
5	$Out2$	Outflow 2	NA
6	$Out3$	Outflow 3	NA
7	$Out4$	Outflow 4	NA

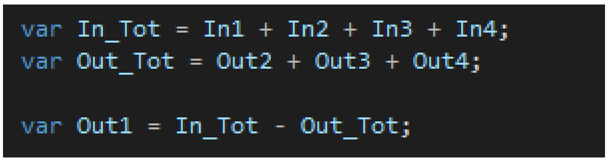
DESCRIPTION OF CALCULATION:

$$MBOutCalc = \sum IN - \sum OUT$$

$$MBOutCalc = (In1 + In2 + In3 + In4) - (Out2 + Out3 + Out4)$$

NOTES: Inflow and outflows to be in the same engineering unit (unit consistency)

C# code:



```
var In_Tot = In1 + In2 + In3 + In4;
var Out_Tot = Out2 + Out3 + Out4;

var Out1 = In_Tot - Out_Tot;
```

3. WMSC01: Station Sent Out

Input:

$\dot{W}_{output}, \dot{W}_{aux}$

n_1, n_2, t, L_f

Calculation:

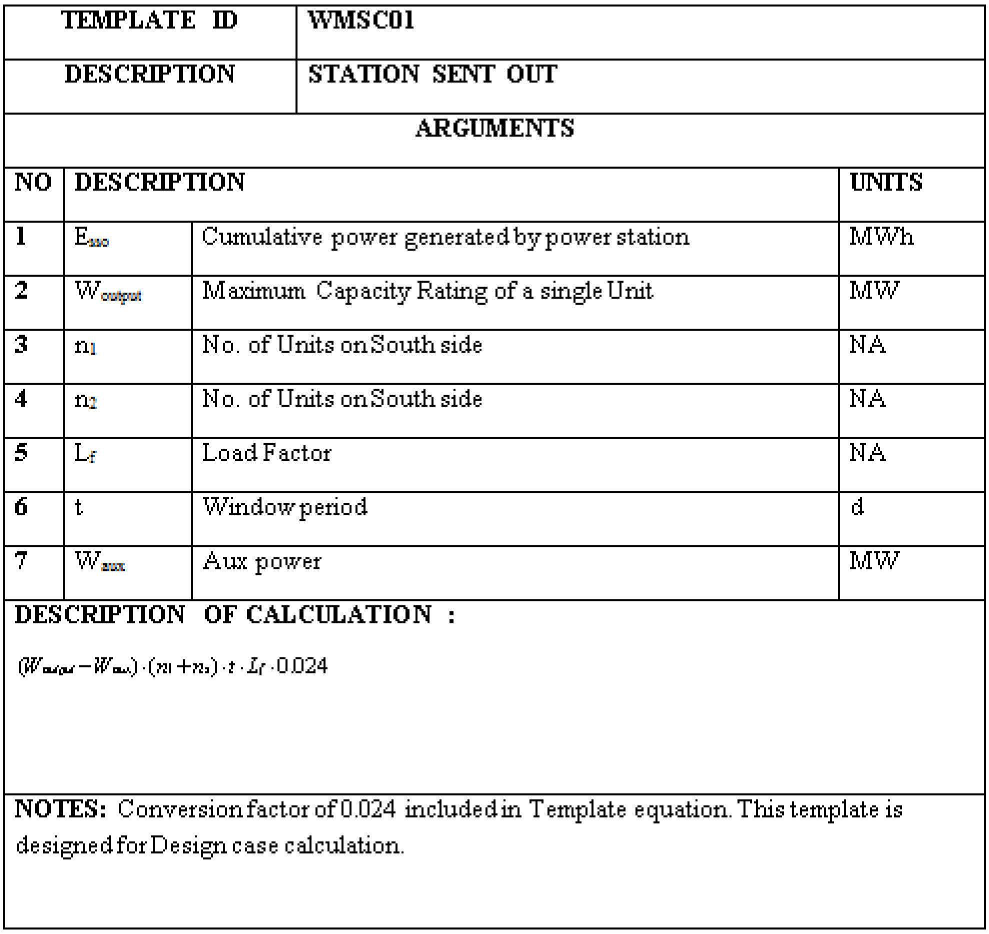
$$E_{sso} = (\dot{W}_{output} - \dot{W}_{aux}) \cdot (n_1 + n_2) \cdot t \cdot L_f \cdot 0.024$$

Output:

E_{sso}

Station Sent Out (GWh)

EtaPRO Calculation Template format:



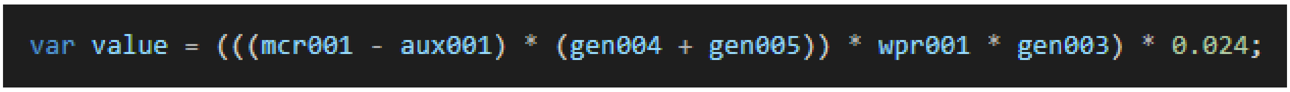
TEMPLATE ID	**WMSC01**		
DESCRIPTION	**STATION SENT OUT**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	E_{sso}	Cumulative power generated by power station	MWh
2	W_{output}	Maximum Capacity Rating of a single Unit	MW
3	n_1	No. of Units on South side	NA
4	n_2	No. of Units on South side	NA
5	L_f	Load Factor	NA
6	t	Window period	d
7	W_{aux}	Aux power	MW

DESCRIPTION OF CALCULATION :

$$(W_{output} - W_{aux}) \cdot (n_1 + n_2) \cdot t \cdot L_f \cdot 0.024$$

NOTES: Conversion factor of 0.024 included in Template equation. This template is designed for Design case calculation.

C# Code:



```
var value = (((mcr001 - aux001) * (gen004 + gen005)) * wpr001 * gen003) * 0.024;
```

4. WMSC02: Mass of total ash produced

Input:

$\dot{W}_{output}, E_{sso}$

n_1, n_2, t, L_f

$\eta_{th}, X_{ash}, CV_{coal}$

Calculation:

$$\dot{m}_{coal} = \frac{\dot{W}_{output} \cdot (n_1 + n_2) \cdot L_f}{CV_{coal} \cdot (\eta_{th} / 100)} \cdot 86.39$$

$$\dot{Q}_{coal} = \frac{\dot{m}_{coal} \cdot t}{E_{sso}}$$

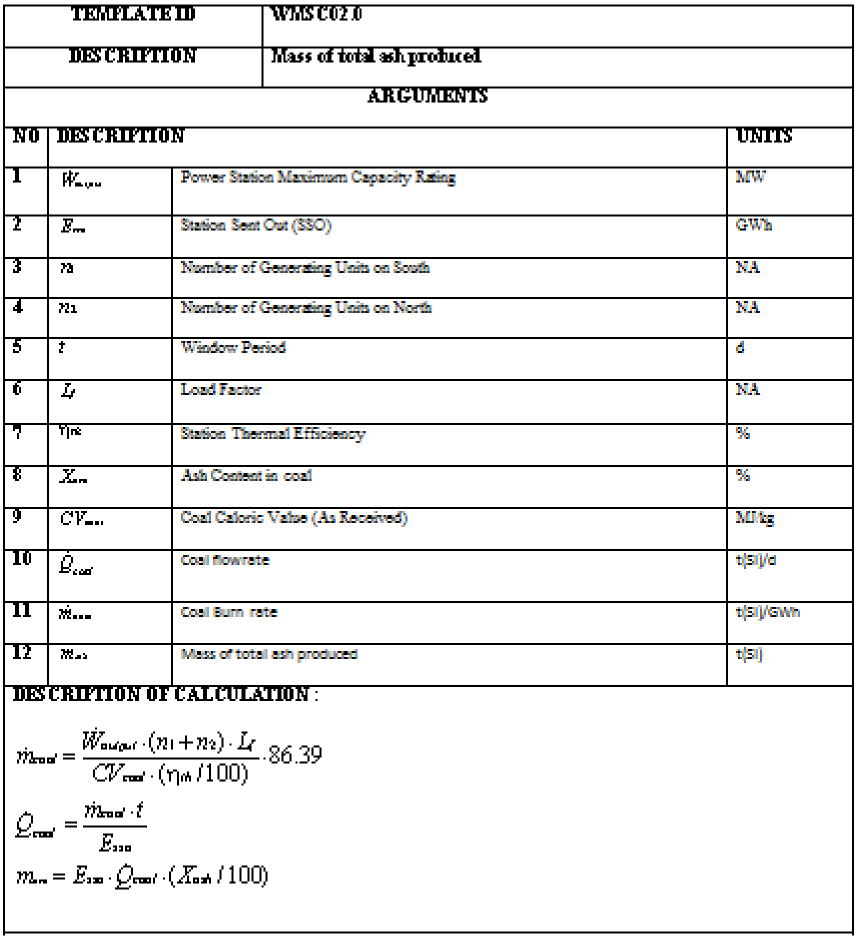
$$m_{ash} = E_{sso} \cdot \dot{Q}_{coal} \cdot (X_{ash} / 100)$$

Output:

m_{ash}

Mass of ash produced (t (SI))

EtaPRO Calculation Template format:



TEMPLATE ID	**WMSC02.0**		
DESCRIPTION	**Mass of total ash produced**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$\dot{W}_{output}$	Power Station Maximum Capacity Rating	MW
2	E_{sso}	Station Sent Out (SSO)	GWh
3	n_2	Number of Generating Units on South	NA
4	n_1	Number of Generating Units on North	NA
5	t	Window Period	d
6	L_f	Load Factor	NA
7	η_{th}	Station Thermal Efficiency	%
8	X_{ash}	Ash Content in coal	%
9	CV_{coal}	Coal Caloric Value (As Received)	MJ/kg
10	$\dot{Q}_{coal}$	Coal flowrate	t(SI)/d
11	$\dot{m}_{coal}$	Coal Burn rate	t(SI)/GWh
12	m_{ash}	Mass of total ash produced	t(SI)

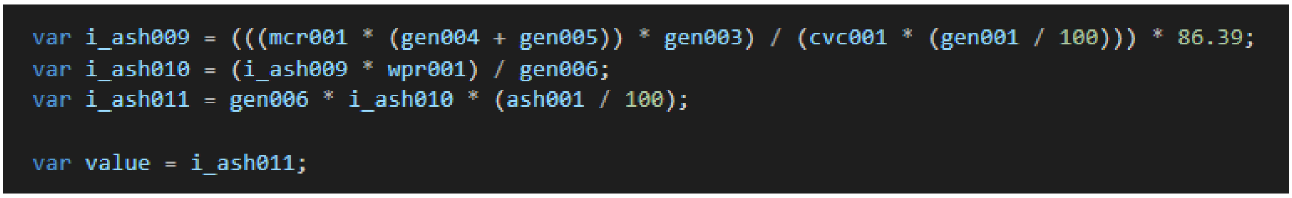
DESCRIPTION OF CALCULATION :

$$\dot{m}_{coal} = \frac{\dot{W}_{output} \cdot (n_1 + n_2) \cdot L_f}{CV_{coal} \cdot (\eta_{th} / 100)} \cdot 86.39$$

$$\dot{Q}_{coal} = \frac{\dot{m}_{coal} \cdot t}{E_{sso}}$$

$$m_{ash} = E_{sso} \cdot \dot{Q}_{coal} \cdot (X_{ash} / 100)$$

C# Code:



```
var i_ash009 = (((mcr001 * (gen004 + gen005)) * gen003) / (cvc001 * (gen001 / 100))) * 86.39;
var i_ash010 = (i_ash009 * wpr001) / gen006;
var i_ash011 = gen006 * i_ash010 * (ash001 / 100);

var value = i_ash011;
```

5. WMSC02.1: Volume of total ash produced

Input:

ρ_{ash}

$\dot{m}_{ash}$

Calculation:

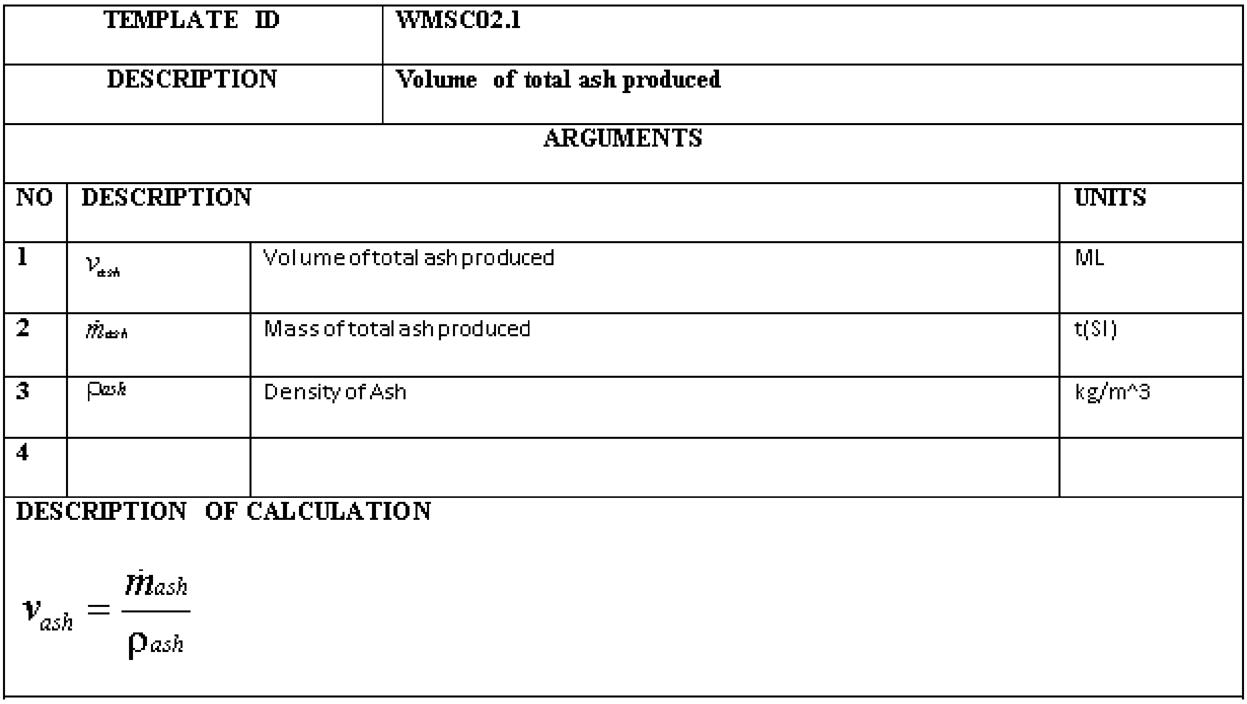
$$v_{ash} = \frac{\dot{m}_{ash}}{\rho_{ash}}$$

Output:

v_{ash}

Volume of ash produced (t (SI))

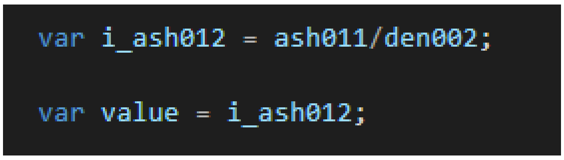
EtaPRO Calculation Template format:



TEMPLATE ID	WMSC02.1		
DESCRIPTION	Volume of total ash produced		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	v_{ash}	Volume of total ash produced	ML
2	$\dot{m}_{ash}$	Mass of total ash produced	t(SI)
3	ρ_{ash}	Density of Ash	kg/m^3
4			
DESCRIPTION OF CALCULATION			

$$v_{ash} = \frac{\dot{m}_{ash}}{\rho_{ash}}$$

C# Code:



```
var i_ash012 = ash011/den002;

var value = i_ash012;
```

6. WMSC02.2: Mass of coarse/Fly ash produced

Input:

m_{ash}

$X_{ash,\,i}$

$i = coarse,\ fly$

Calculation:

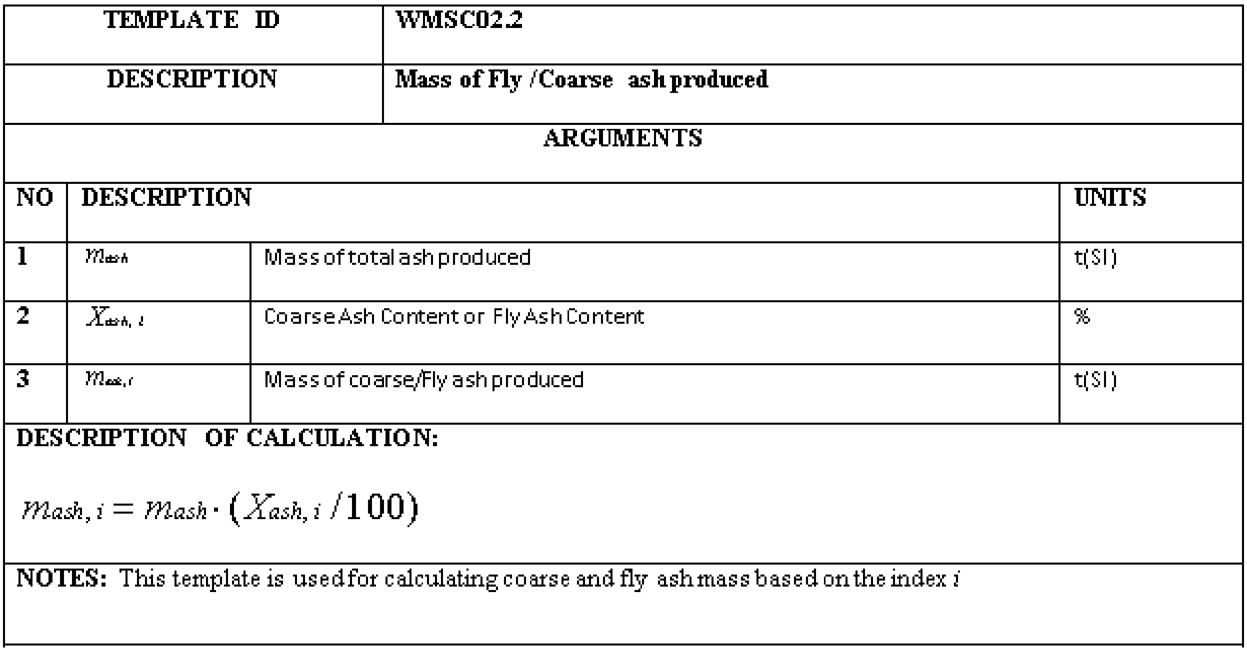
$$m_{ash,\,i} = m_{ash} \cdot (X_{ash,\,i} / 100)$$

Output:

$m_{ash,\,i}$

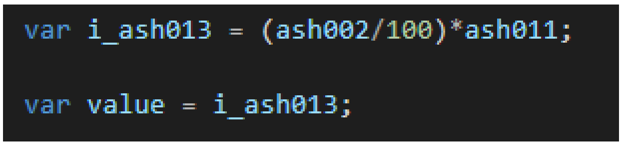
Mas of fly or coarse ash produced (t (SI))

EtaPRO Calculation Template format:



<table>
<tr><td colspan="2">TEMPLATE ID</td><td colspan="2">WMSC02.2</td></tr>
<tr><td colspan="2">DESCRIPTION</td><td colspan="2">Mass of Fly /Coarse ash produced</td></tr>
<tr><td colspan="4">ARGUMENTS</td></tr>
<tr><td>NO</td><td colspan="2">DESCRIPTION</td><td>UNITS</td></tr>
<tr><td>1</td><td>m_{ash}</td><td>Mass of total ash produced</td><td>t(SI)</td></tr>
<tr><td>2</td><td>$X_{ash,\,i}$</td><td>Coarse Ash Content or Fly Ash Content</td><td>%</td></tr>
<tr><td>3</td><td>$m_{ash,\,i}$</td><td>Mass of coarse/Fly ash produced</td><td>t(SI)</td></tr>
<tr><td colspan="4">DESCRIPTION OF CALCULATION:
$m_{ash,\,i} = m_{ash} \cdot (X_{ash,\,i} / 100)$</td></tr>
<tr><td colspan="4">NOTES: This template is used for calculating coarse and fly ash mass based on the index i</td></tr>
</table>

C# Code:



```
var i_ash013 = (ash002/100)*ash011;

var value = i_ash013;
```

7. WMSC02.3: Total water absorbed on ash dam

Input:

$m_{ash,\ coarse}$

$m_{ash,\ fly}$

ρ_w

AIH

Calculation:

$$v_{ash.coarse} = \frac{m_{ash,\ coarse} \cdot AIH}{\rho_w}$$

$$v_{ash.\ fly} = \frac{m_{ash.\ fly} \cdot AIH}{\rho_w}$$

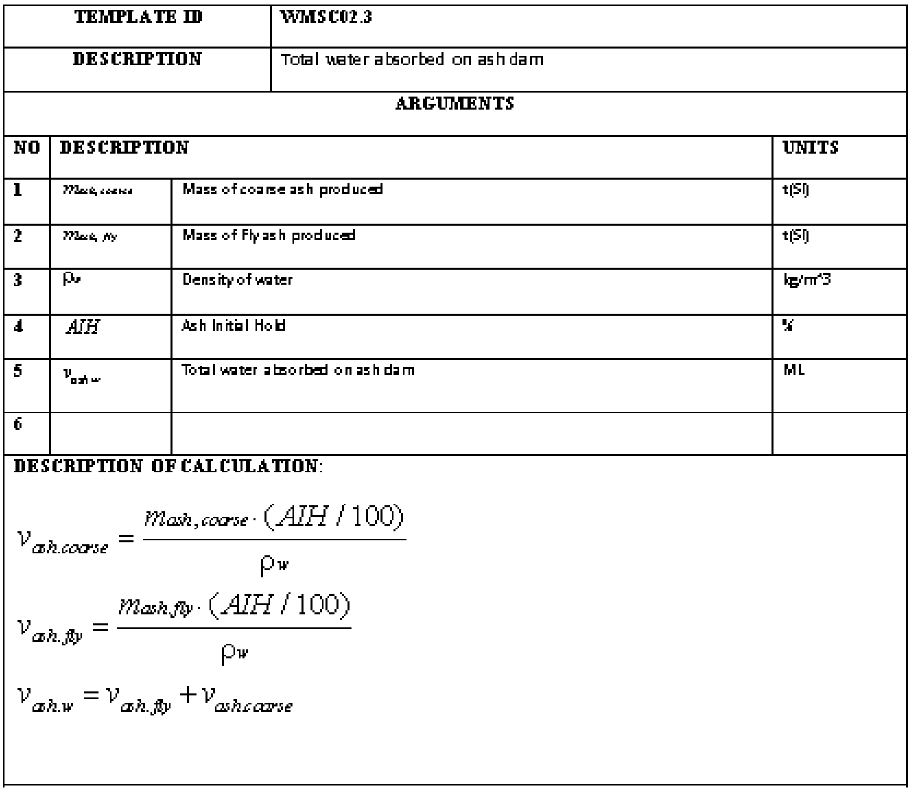
$$v_{ash.w} = v_{ash.\ fly} + v_{ash.coarse}$$

Output:

$v_{ash.w}$

Volume of water absorbed on ash dam (Ml)

EtaPRO Calculation Template format:



TEMPLATE ID	**WMSC02.3**		
DESCRIPTION	Total water absorbed on ash dam		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$m_{ash,coarse}$	Mass of coarse ash produced	t(SI)
2	$m_{ash,fly}$	Mass of Fly ash produced	t(SI)
3	ρ_w	Density of water	kg/m^3
4	AIH	Ash Initial Hold	%
5	$v_{ash.w}$	Total water absorbed on ash dam	ML
6			

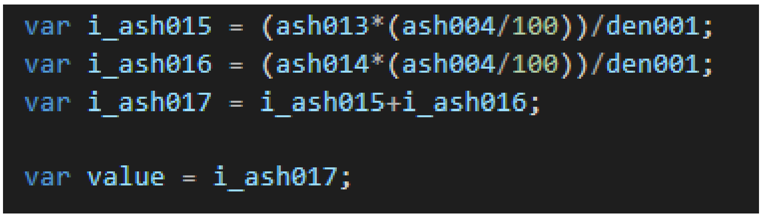
DESCRIPTION OF CALCULATION:

$$v_{ash.coarse} = \frac{m_{ash,coarse} \cdot (AIH / 100)}{\rho_w}$$

$$v_{ash.fly} = \frac{m_{ash.fly} \cdot (AIH / 100)}{\rho_w}$$

$$v_{ash.w} = v_{ash.fly} + v_{ash.coarse}$$

C# Code:



```
var i_ash015 = (ash013*(ash004/100))/den001;
var i_ash016 = (ash014*(ash004/100))/den001;
var i_ash017 = i_ash015+i_ash016;

var value = i_ash017;
```

8. WMSC03: Total Cooling Tower make-up requirement

Input:

E_{sso}

I_E

I_D

η_d

η_a

Calculation:

$$v_E = E_{sso} \cdot I_E$$

$$v_D = E_{sso} \cdot I_D$$

$$v_{cf} = (\eta_d - \eta_a) \cdot E_{uso} \cdot 0.04 \frac{L}{kWh}$$

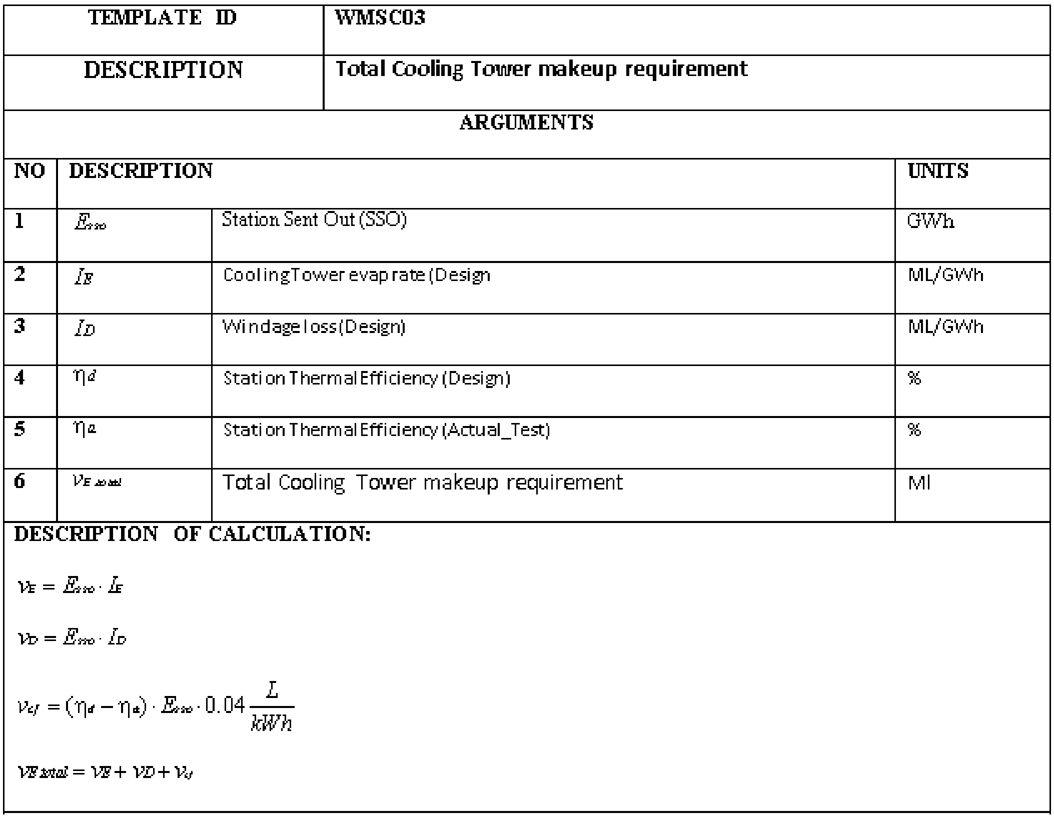
$$v_{E.total} = v_E + v_D + v_{cf}$$

Output:

$v_{E.total}$

Total Cooling Tower makeup requirement (Ml)

EtaPRO Calculation Template format:



TEMPLATE ID	WMSC03		
DESCRIPTION	Total Cooling Tower makeup requirement		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	E_{sso}	Station Sent Out (SSO)	GWh
2	I_E	Cooling Tower evap rate (Design	ML/GWh
3	I_D	Windage loss (Design)	ML/GWh
4	η_d	Station Thermal Efficiency (Design)	%
5	η_a	Station Thermal Efficiency (Actual_Test)	%
6	$v_{E.total}$	Total Cooling Tower makeup requirement	Ml

DESCRIPTION OF CALCULATION:

$$v_E = E_{sso} \cdot I_E$$

$$v_D = E_{sso} \cdot I_D$$

$$v_{cf} = (\eta_d - \eta_a) \cdot E_{sso} \cdot 0.04 \frac{L}{kWh}$$

$$v_{E.total} = v_E + v_D + v_{cf}$$

C# Code:

```
var value = ((gen001  - gen002 ) * 0.04 * gen006) + (gen006 * evp002) + (gen006 * evp003);
```

9. WMSC04: Rain collection on dams

Input:

i

A

t

Calculation:

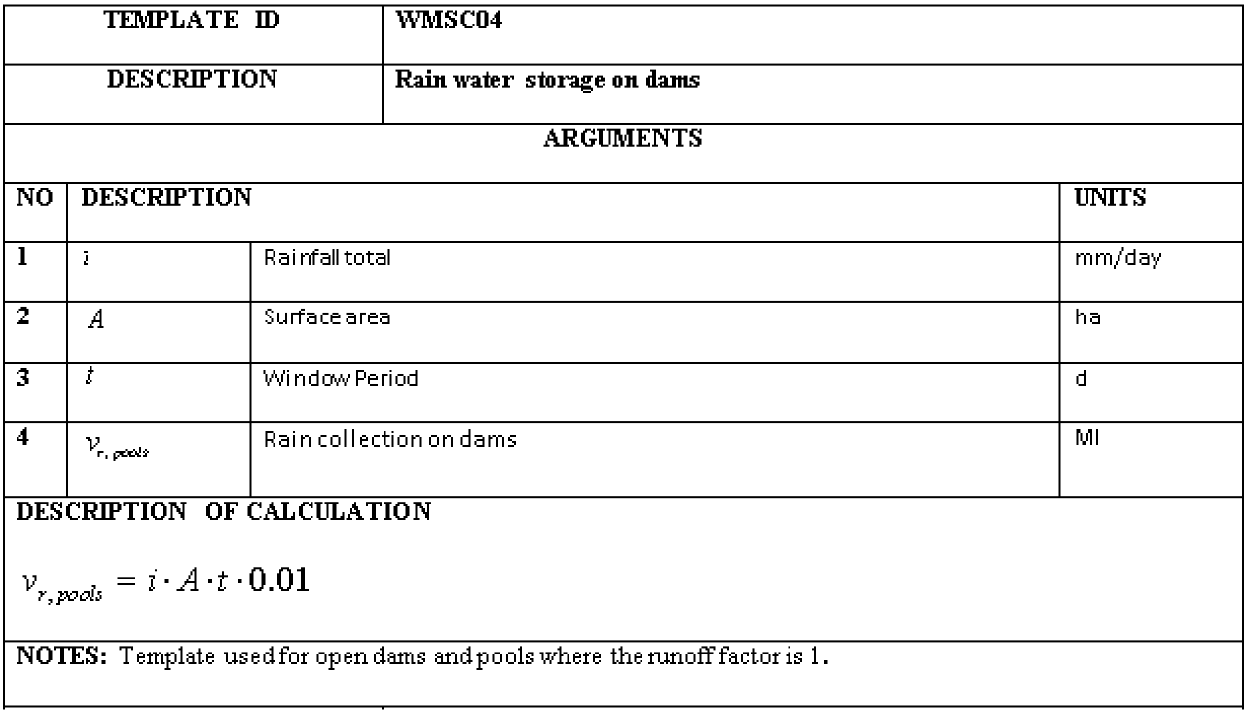
$$v_{r,pools} = i \cdot A \cdot t \cdot 0.01$$

Output:

$v_{r,pools}$

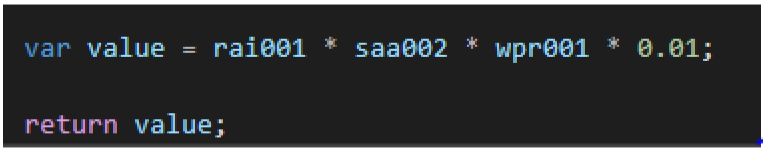
Rain collection on dams (Ml)

EtaPRO Calculation Template format:



TEMPLATE ID	**WMSC04**		
DESCRIPTION	**Rain water storage on dams**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	i	Rainfall total	mm/day
2	A	Surface area	ha
3	t	Window Period	d
4	$v_{r,pools}$	Rain collection on dams	Ml
DESCRIPTION OF CALCULATION $v_{r,pools} = i \cdot A \cdot t \cdot 0.01$			
NOTES: Template used for open dams and pools where the runoff factor is 1.			

C# Code:



```
var value = rai001 * saa002 * wpr001 * 0.01;

return value;
```

10. WMSC05: Rain run-off (Station terrace/dams)

Input:

i

A

t

f_r

Calculation:

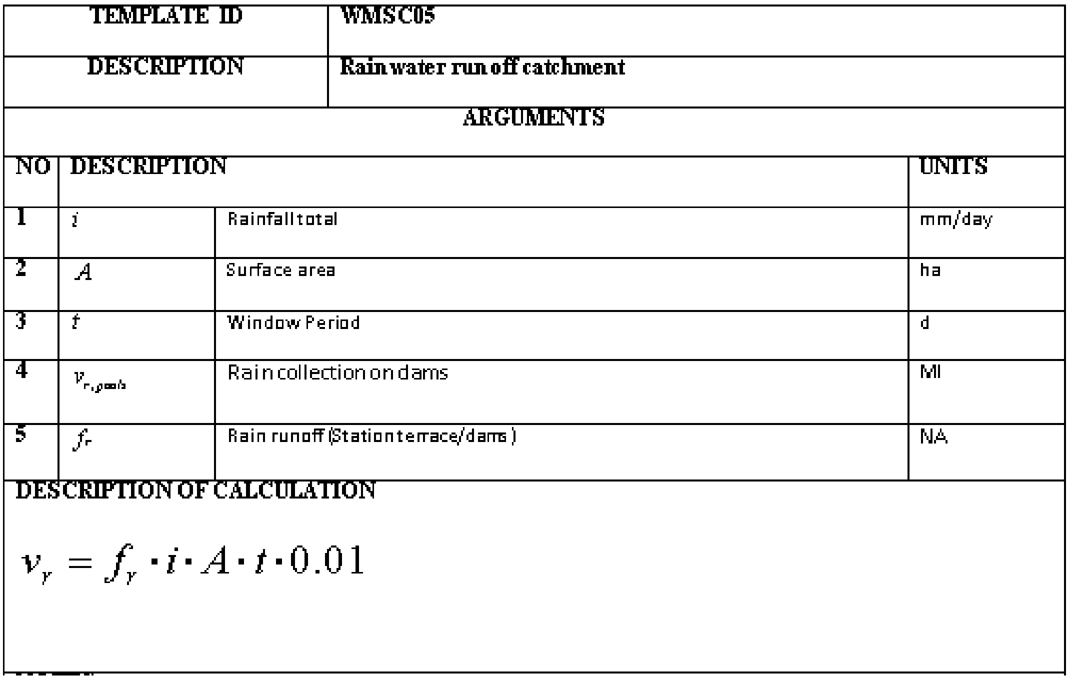
$$v_r = f_r \cdot i \cdot A \cdot t \cdot 0.01$$

Output:

v_r

Rain run-off (Ml)

EtaPRO Calculation Template format:

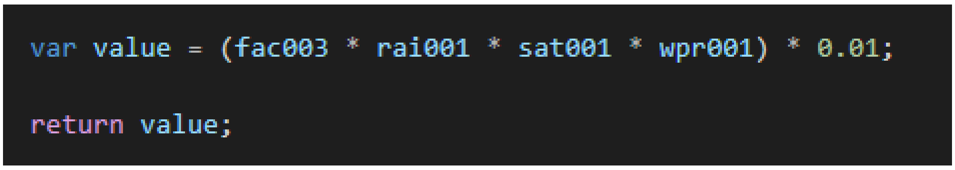


TEMPLATE ID	WMSC05		
DESCRIPTION	Rain water run off catchment		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	i	Rainfall total	mm/day
2	A	Surface area	ha
3	t	Window Period	d
4	$v_{r,pools}$	Rain collection on dams	Ml
5	f_r	Rain runoff (Station terrace/dams)	NA

DESCRIPTION OF CALCULATION

$$v_r = f_r \cdot i \cdot A \cdot t \cdot 0.01$$

C# Code:



```
var value = (fac003 * rai001 * sat001 * wpr001) * 0.01;

return value;
```

11. WMSC06: Evaporation from ash dam pool

Input:

e_i

A

t

$i : dampool$

Calculation:

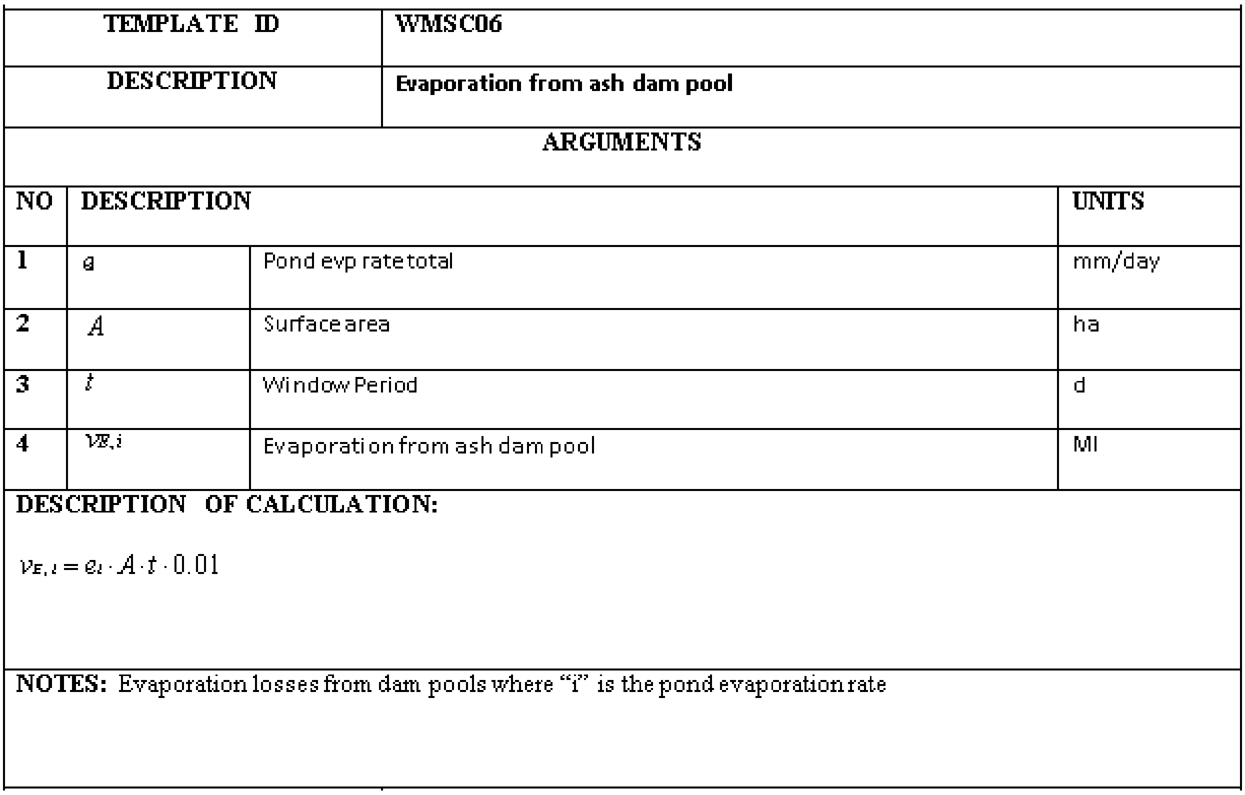
$$v_{E,i} = e_i \cdot A \cdot t \cdot 0.01$$

Output:

$v_{E,i}$

Evaporation from ash dam pool (Ml)

EtaPRO Calculation Template format:



TEMPLATE ID	**WMSC06**		
DESCRIPTION	**Evaporation from ash dam pool**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	e_i	Pond evp rate total	mm/day
2	A	Surface area	ha
3	t	Window Period	d
4	$v_{E,i}$	Evaporation from ash dam pool	Ml
DESCRIPTION OF CALCULATION: $v_{E,i} = e_i \cdot A \cdot t \cdot 0.01$			
NOTES: Evaporation losses from dam pools where "i" is the pond evaporation rate			

C# Code:

```
var value = saa002 * evp005 * wpr001 * 0.01;

return value;
```

12. WMSC07: Evaporation from Ash dam/CSY

Input:

e_i

A

t

$i : ashphase$

Calculation:

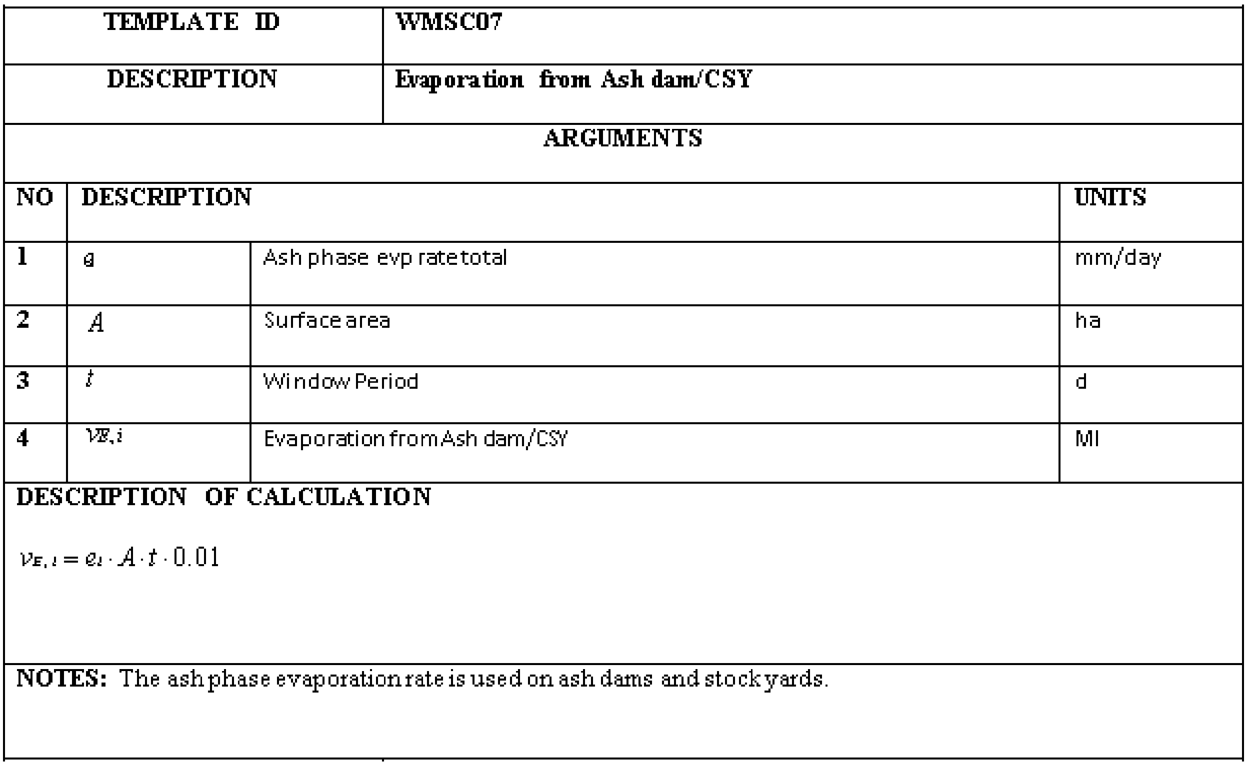
$$v_{E,i} = e_i \cdot A \cdot t \cdot 0.01$$

Output:

$v_{E,i}$

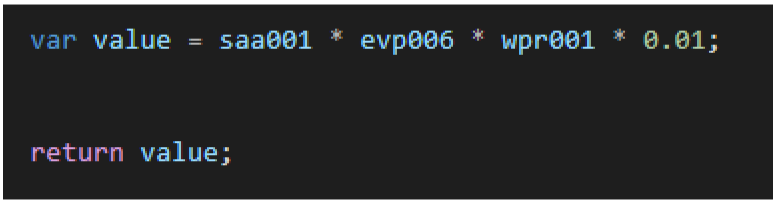
Evaporation from Ash dam/CSY (Ml)

EtaPRO Calculation Template format:



TEMPLATE ID	WMSC07		
DESCRIPTION	Evaporation from Ash dam/CSY		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	e_i	Ash phase evp rate total	mm/day
2	A	Surface area	ha
3	t	Window Period	d
4	$v_{E,i}$	Evaporation from Ash dam/CSY	Ml
DESCRIPTION OF CALCULATION $v_{E,i} = e_i \cdot A \cdot t \cdot 0.01$			
NOTES: The ash phase evaporation rate is used on ash dams and stock yards.			

C# Code:



```
var value = saa001 * evp006 * wpr001 * 0.01;


return value;
```

13. WMSC08: Evaporation from Coarse Ash Quenching

Input:

$m_{ash,\,coarse}$

ρ_w

f_q

Calculation:

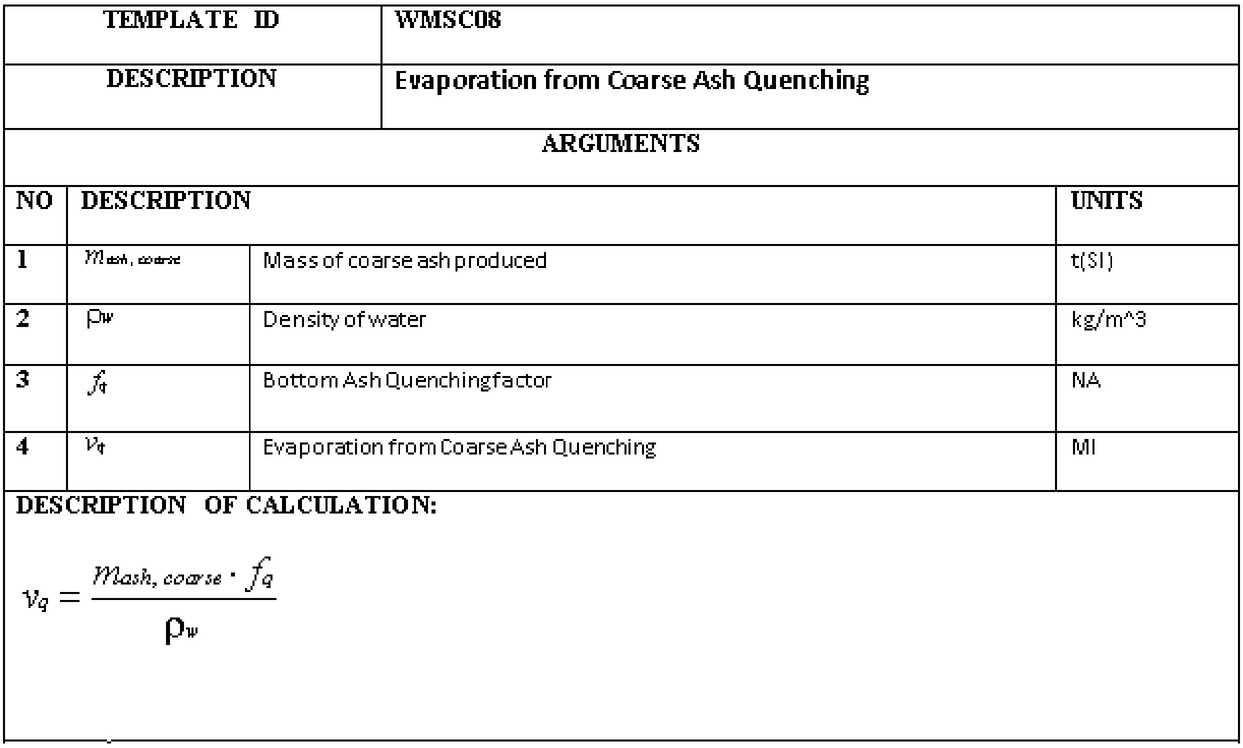
$$v_q = \frac{m_{ash,\,coarse} \cdot f_q}{\rho_w}$$

Output:

v_q

Evaporation from Coarse Ash Quenching (Ml)

EtaPRO Calculation Template format:

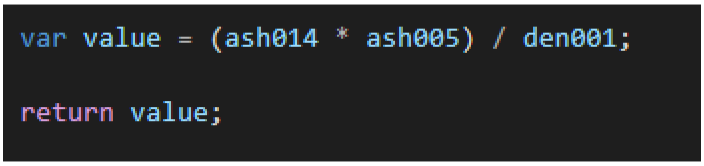


TEMPLATE ID		**WMSC08**	
DESCRIPTION		**Evaporation from Coarse Ash Quenching**	
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$m_{ash,\,coarse}$	Mass of coarse ash produced	t(SI)
2	ρ_w	Density of water	kg/m^3
3	f_q	Bottom Ash Quenching factor	NA
4	v_q	Evaporation from Coarse Ash Quenching	Ml

DESCRIPTION OF CALCULATION:

$$v_q = \frac{m_{ash,\,coarse} \cdot f_q}{\rho_w}$$

C# Code:



```
var value = (ash014 * ash005) / den001;

return value;
```

14. WMSC010: Water Performance

Input:

v_{raw}

$\dot{W}_{net}$

t

Calculation:

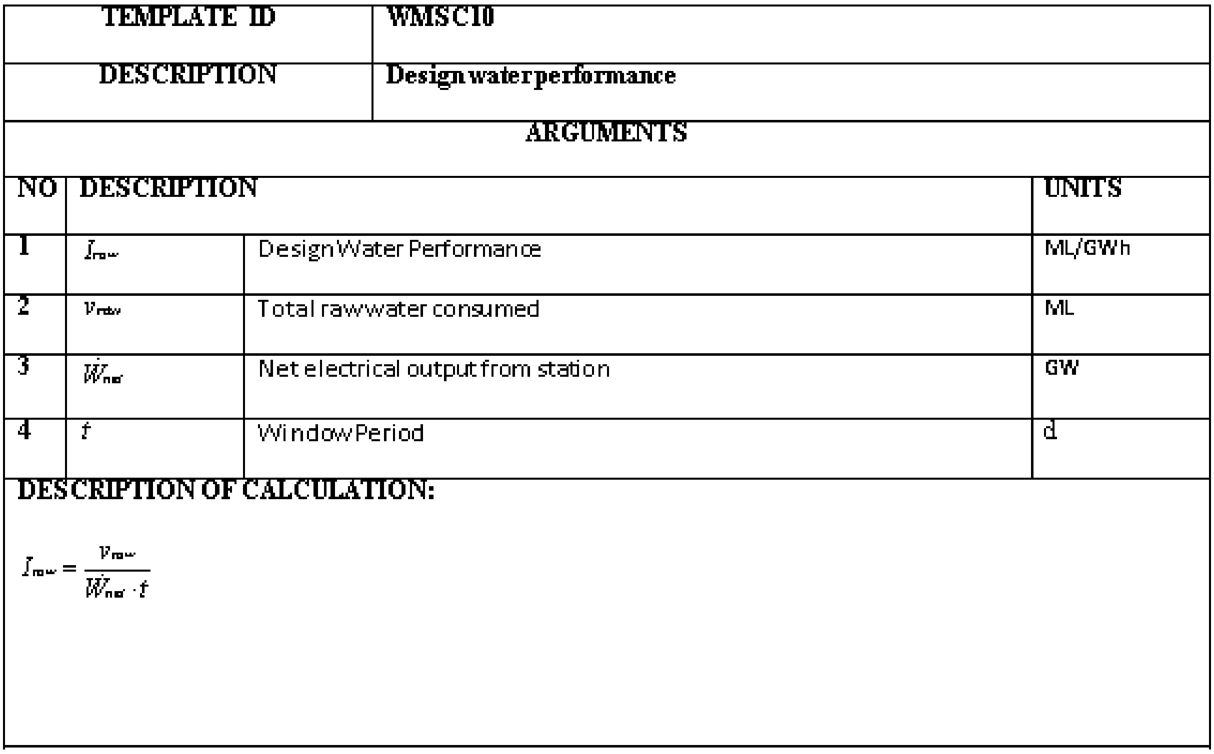
$$I_{raw} = \frac{v_{raw}}{\dot{W}_{net} \cdot t}$$

Output:

I_{raw}

Water Performance (ML/GWh)

EtaPRO Calculation Template format:

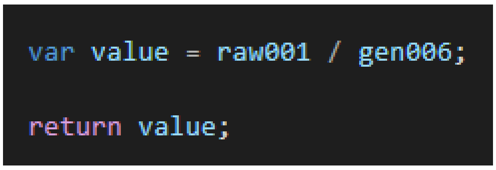


TEMPLATE ID	**WMSC10**		
DESCRIPTION	**Design water performance**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	I_{raw}	Design Water Performance	ML/GWh
2	v_{raw}	Total raw water consumed	ML
3	$\dot{W}_{net}$	Net electrical output from station	GW
4	t	Window Period	d

DESCRIPTION OF CALCULATION:

$$I_{raw} = \frac{v_{raw}}{\dot{W}_{net} \cdot t}$$

C# Code:



```
var value = raw001 / gen006;

return value;
```

15. WMSC012: Cycles of concentration

Input:

$C_{Limit,i}$

$C_{M,i}$

Dosing Type

Calculation:

$$N = \frac{C_{Limit,i}}{C_{M,i}}, \; N = \sqrt{\frac{C_{Limit,ij}}{C_{M,i} \cdot C_{M,j}}}$$

Output:

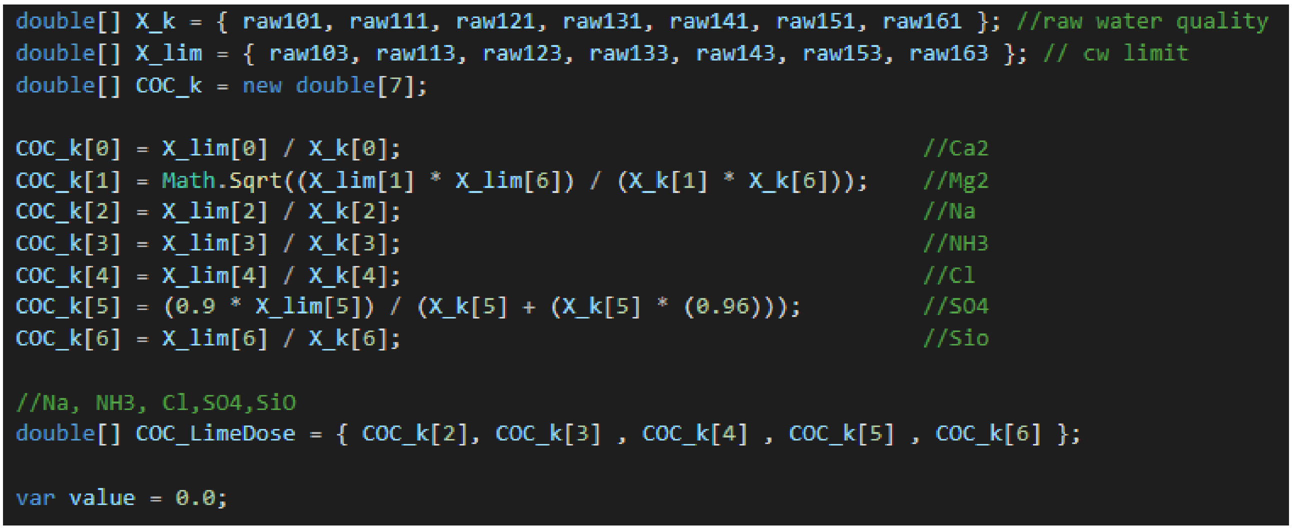
N

Cycles of Concentration

EtaPRO Calculation Template format:

TEMPLATE ID	**WMSC12**		
DESCRIPTION	**Cycles of concentration (COC)**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	N	Cycles of concentration (COC)	NA
2	$C_{Limit,i}$	Raw water quality Limit for species "i"	mg/L
3	$C_{M,i}$	Raw water quality Limit for species "i"	mg/L
4	Dos	Dosing selection (Lime, Acid, None)	NA
DESCRIPTION OF CALCULATION $N = \frac{C_{Limit,i}}{C_{M,i}}$ For ion pair calculation: $N = \sqrt{\frac{C_{Limit,ij}}{C_{M,i} \cdot C_{M,j}}}$ $N = \min(N_i)$			
NOTES: The COC is calculation is based on raw water raw quality input for Ca_2, Mg_2, Na, NH_3, Cl, SO_4, SiO, M.alk.			

C# Code:

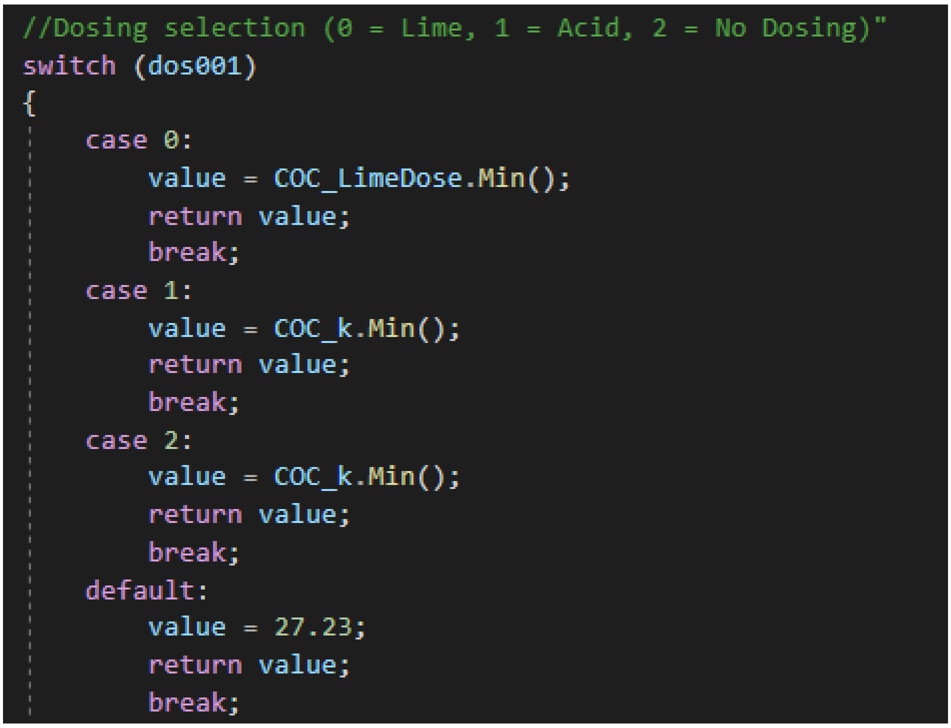


```
double[] X_k = { raw101, raw111, raw121, raw131, raw141, raw151, raw161 }; //raw water quality
double[] X_lim = { raw103, raw113, raw123, raw133, raw143, raw153, raw163 }; // cw limit
double[] COC_k = new double[7];

COC_k[0] = X_lim[0] / X_k[0];                                       //Ca2
COC_k[1] = Math.Sqrt((X_lim[1] * X_lim[6]) / (X_k[1] * X_k[6]));    //Mg2
COC_k[2] = X_lim[2] / X_k[2];                                       //Na
COC_k[3] = X_lim[3] / X_k[3];                                       //NH3
COC_k[4] = X_lim[4] / X_k[4];                                       //Cl
COC_k[5] = (0.9 * X_lim[5]) / (X_k[5] + (X_k[5] * (0.96)));         //SO4
COC_k[6] = X_lim[6] / X_k[6];                                       //Sio

//Na, NH3, Cl,SO4,SiO
double[] COC_LimeDose = { COC_k[2], COC_k[3] , COC_k[4] , COC_k[5] , COC_k[6] };

var value = 0.0;
```



```
//Dosing selection (0 = Lime, 1 = Acid, 2 = No Dosing)"
switch (dos001)
{
    case 0:
        value = COC_LimeDose.Min();
        return value;
        break;
    case 1:
        value = COC_k.Min();
        return value;
        break;
    case 2:
        value = COC_k.Min();
        return value;
        break;
    default:
        value = 27.23;
        return value;
        break;
```

16. WMSC013: CW Clarifier Blowdown

Input:

N

$\dot{v}_E$

Calculation:

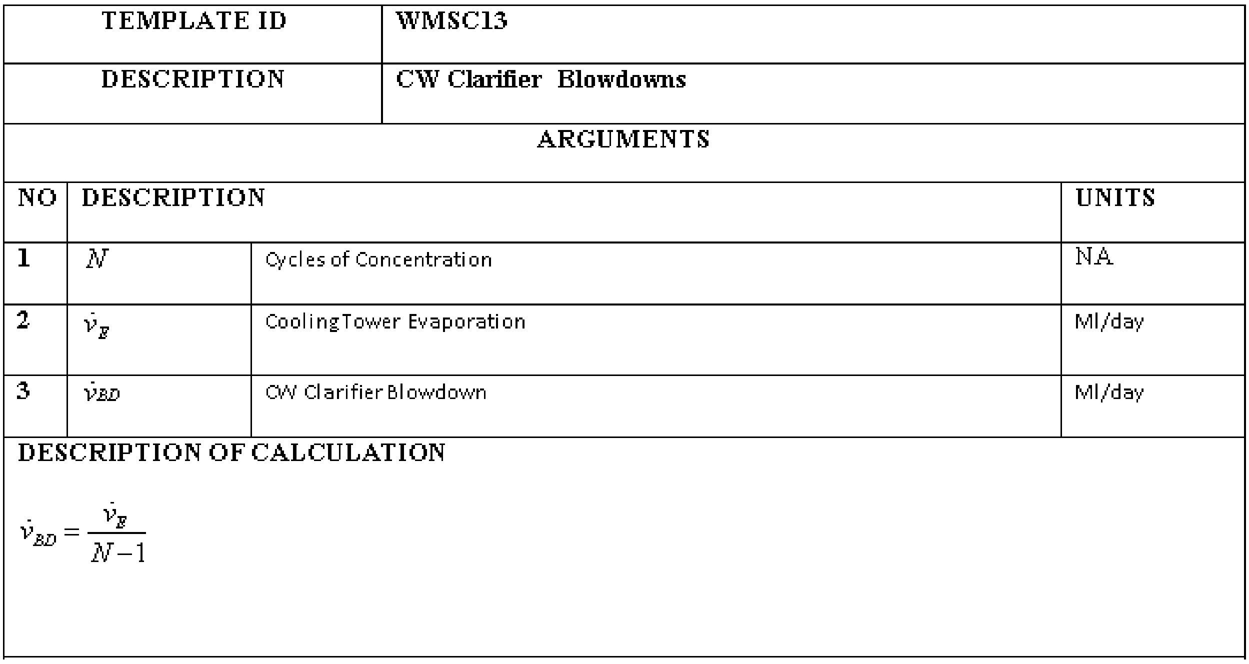
$$\dot{v}_{BD} = \frac{\dot{v}_E}{N-1}$$

Output:

$\dot{v}_{BD}$

CW Clarifier Blowdown (Ml/day)

EtaPRO Calculation Template format:

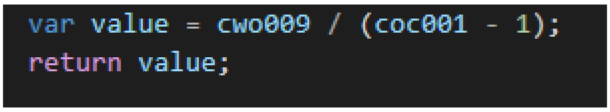


TEMPLATE ID	WMSC13		
DESCRIPTION	CW Clarifier Blowdowns		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	N	Cycles of Concentration	NA
2	$\dot{v}_E$	Cooling Tower Evaporation	Ml/day
3	$\dot{v}_{BD}$	CW Clarifier Blowdown	Ml/day

DESCRIPTION OF CALCULATION

$$\dot{v}_{BD} = \frac{\dot{v}_E}{N-1}$$

C# Code:



```
var value = cwo009 / (coc001 - 1);
return value;
```

17. WMSC014: Raw Clarifier Blowdown

Input:

$\dot{v}_{cl.out}$

T

P_s

ρ_w

Calculation:

$$f_2 = \frac{T \cdot \frac{1}{3}\frac{mg}{l}}{P_s \cdot \rho_w}$$

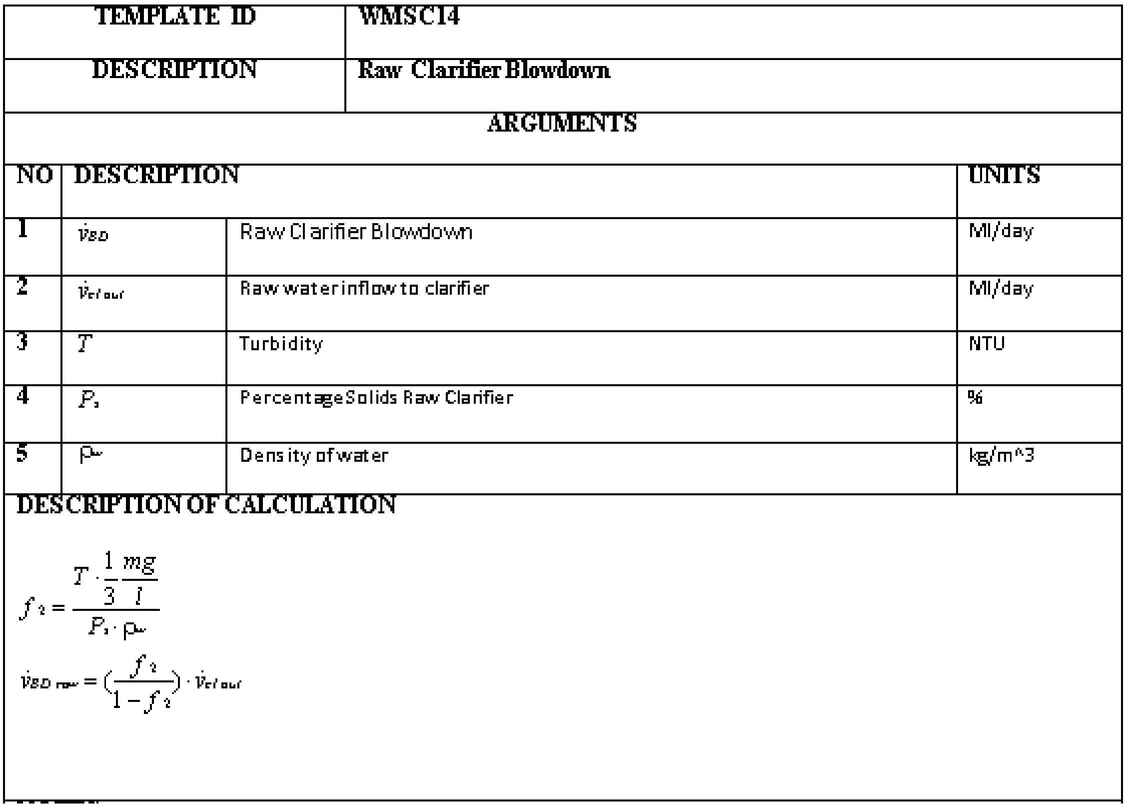
$$\dot{v}_{BD.raw} = (\frac{f_2}{1 - f_2}) \cdot \dot{v}_{cl.out}$$

Output:

$\dot{v}_{BD.raw}$

Raw Clarifier Blowdown (Ml/day)

EtaPRO Calculation Template format:



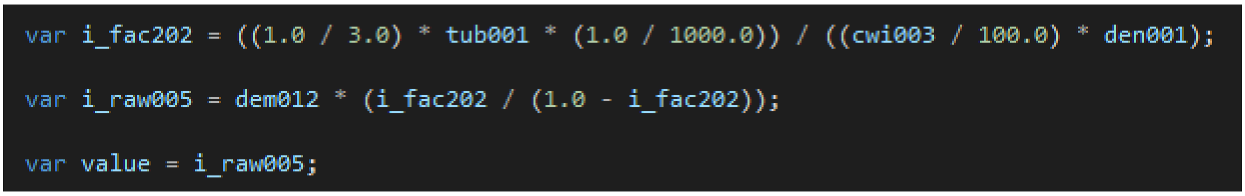
TEMPLATE ID	**WMSC14**		
DESCRIPTION	**Raw Clarifier Blowdown**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$\dot{v}_{BD}$	Raw Clarifier Blowdown	Ml/day
2	$\dot{v}_{cl\,out}$	Raw water inflow to clarifier	Ml/day
3	T	Turbidity	NTU
4	P_s	Percentage Solids Raw Clarifier	%
5	ρ_w	Density of water	kg/m^3

DESCRIPTION OF CALCULATION

$$f_2 = \frac{T \cdot \frac{1}{3}\frac{mg}{l}}{P_s \cdot \rho_w}$$

$$\dot{v}_{BD\,raw} = (\frac{f_2}{1 - f_2}) \cdot \dot{v}_{cl\,out}$$

C# Code:



```
var i_fac202 = ((1.0 / 3.0) * tub001 * (1.0 / 1000.0)) / ((cwi003 / 100.0) * den001);

var i_raw005 = dem012 * (i_fac202 / (1.0 - i_fac202));

var value = i_raw005;
```

18. WMSC015: WTP total effluent

Input:

$v_{dem.cap}$

$\dot{v}_{dem}$

$v_{dem.regen}$

n_{regen}

$v_{cpp.regen}$

Calculation:

$$\dot{v}_{eff.dem} = \frac{\dot{v}_{dem}}{v_{dem.cap}} \cdot v_{dem.regen}$$

$$\dot{v}_{eff.cpp} = \frac{n_{regen} \cdot v_{cpp.regen}}{1000}$$

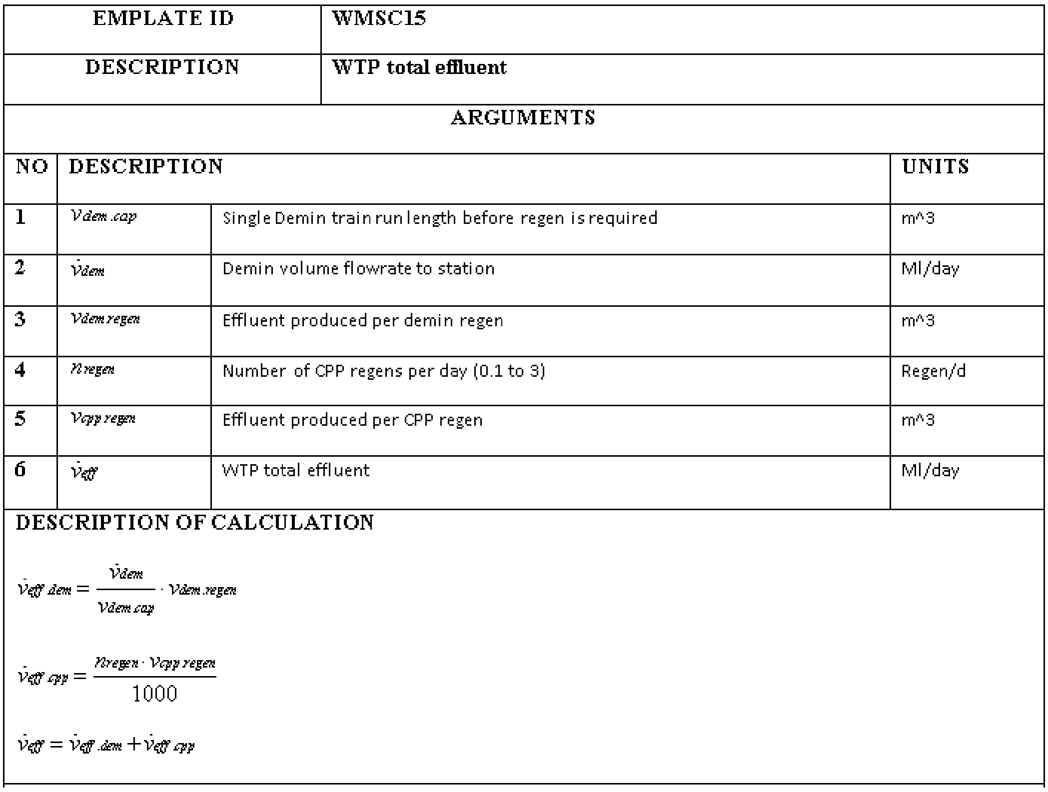
$$\dot{v}_{eff} = \dot{v}_{eff.dem} + \dot{v}_{eff.cpp}$$

Output:

$\dot{v}_{eff}$

WTP total effluent (Ml/day)

EtaPRO Calculation Template format:



EMPLATE ID	WMSC15		
DESCRIPTION	WTP total effluent		
ARGUMENTS			
NO	DESCRIPTION		UNITS
1	$v_{dem.cap}$	Single Demin train run length before regen is required	m^3
2	$\dot{v}_{dem}$	Demin volume flowrate to station	Ml/day
3	$v_{dem.regen}$	Effluent produced per demin regen	m^3
4	n_{regen}	Number of CPP regens per day (0.1 to 3)	Regen/d
5	$v_{cpp.regen}$	Effluent produced per CPP regen	m^3
6	$\dot{v}_{eff}$	WTP total effluent	Ml/day

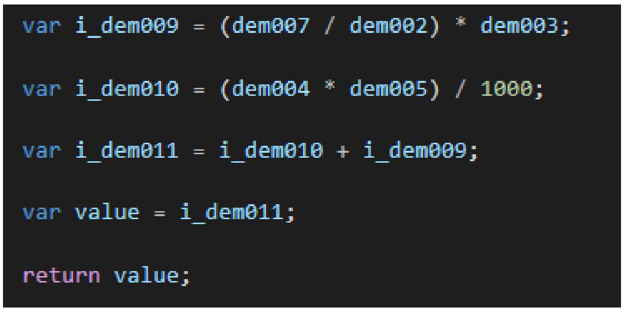
DESCRIPTION OF CALCULATION

$$\dot{v}_{eff.dem} = \frac{\dot{v}_{dem}}{v_{dem.cap}} \cdot v_{dem.regen}$$

$$\dot{v}_{eff.cpp} = \frac{n_{regen} \cdot v_{cpp.regen}}{1000}$$

$$\dot{v}_{eff} = \dot{v}_{eff.dem} + \dot{v}_{eff.cpp}$$

C# Code:



```
var i_dem009 = (dem007 / dem002) * dem003;

var i_dem010 = (dem004 * dem005) / 1000;

var i_dem011 = i_dem010 + i_dem009;

var value = i_dem011;

return value;
```

19. WMSC018: Total water required for Ashing

Input:

ρ_w, ρ_{ash}

v_{ash}, t

R_{a_w}

Calculation:

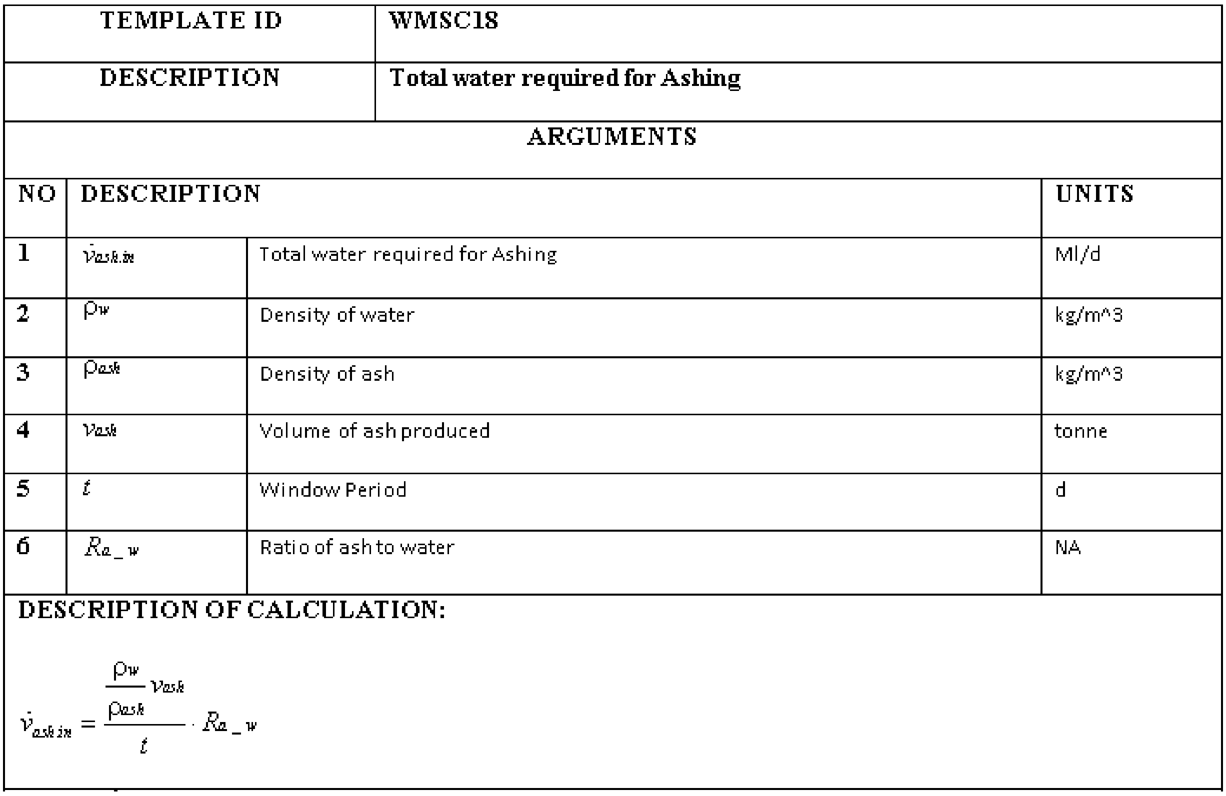
$$\dot{v}_{ash.in} = \frac{\frac{\rho_w}{\rho_{ash}} v_{ash}}{t} \cdot R_{a\_w}$$

Output:

$\dot{v}_{ash.in}$

Total water required for Ashing (Ml/day)

EtaPRO Calculation Template format:

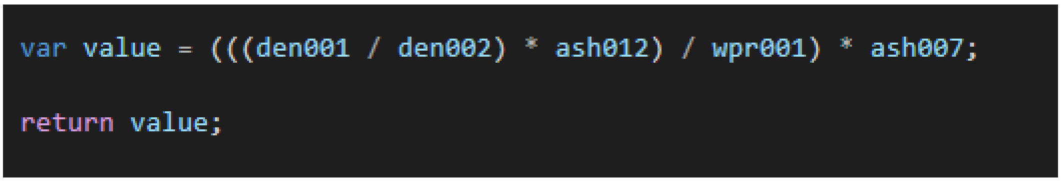


TEMPLATE ID	**WMSC18**		
DESCRIPTION	**Total water required for Ashing**		
ARGUMENTS			
NO	**DESCRIPTION**		**UNITS**
1	$\dot{v}_{ash.in}$	Total water required for Ashing	Ml/d
2	ρ_w	Density of water	kg/m^3
3	ρ_{ash}	Density of ash	kg/m^3
4	v_{ash}	Volume of ash produced	tonne
5	t	Window Period	d
6	R_{a_w}	Ratio of ash to water	NA

DESCRIPTION OF CALCULATION:

$$\dot{v}_{ash.in} = \frac{\frac{\rho_w}{\rho_{ash}} v_{ash}}{t} \cdot R_{a\_w}$$

C# Code:



```
var value = (((den001 / den002) * ash012) / wpr001) * ash007;

return value;
```