Simulating and Optimising the Operation of Integrated Water Resource and Electricity Supply Systems in Africa

Daniel Mulatu (EEPCO - Ethiopia), Christian Msyani (TANESCO – Tanzania)
Andrew Pearce (Parsons Brinckerhoff – UK), Timothy Wyatt (PWSC – UK)

Ever increasing demands for water and electricity make it vital that, as elsewhere in the world, supply systems in Africa are operated as efficiently as possible. Similarly, plans for the optimal development of such systems need to take adequate account of operational aspects.

Continuing advances in computer capabilities now make it possible to simulate the performance of complex supply systems with greater levels of detail, to employ robust mathematical programming algorithms to optimise their long and short-term operation, and to present the results in ways that are more transparent and easier to interpret.

This paper describes ways in which such capabilities can be exploited to improve decision making processes, and discusses a number of modelling aspects that bear on the accuracy that can be ascribed to the results of simulation and optimisation studies. Examples are presented based on recent modelling of existing and potential systems in Ethiopia and Tanzania.

Computer Program Development

During the 1970's and 1980's a number of generalised computer programs were developed to assist in planning the operation and development of large scale water and electricity supply systems. Although initially designed to execute on 'mainframe' computers, several were developed to run on mini and Personal Computers (PC's) and continue to see extensive use.

Examples of software for simulating the operation of water resource systems include the HEC-5 program developed by the US Army Corps of Engineers and its derivative, the ARSP program of the Canadian firm ACRES International. Both have been widely used to study the operation of multi-purpose systems, including those required to supply the often conflicting requirements of irrigation and hydropower generation, with reservoir releases in each time step being determined according to user defined long-term operating policies. For computational reasons, most applications have employed a monthly time step and, while neither program attempts to represent other types of electricity generation or perform load dispatch simulations, their outputs have frequently been used to specify the capabilities of existing and potential hydropower plants as required for expansion planning purposes.

The Wien Automatic System Planning (WASP) series of computer software continues to be employed by many national electricity utilities to plan the expansion of their electricity generation systems. Originally developed in the United States by the Tennessee Valley Authority and the Oak Ridge National Laboratory for the International Atomic Energy Agency (IAEA), the capabilities of WASP have been steadily enhanced, particularly in relation to the modelling of hydropower facilities. However, while WASP incorporates probabilistic load dispatch simulation routines and a dynamic programming based sequencing algorithm, it has long been recognised that the underlying methodology cannot, for example, guarantee the optimal selection and construction timing of candidate hydro plants.

While PC (MS-DOS) versions of HEC-5, ARSP and WASP subsequently became available, their modelling scope and overall capabilities were not significantly enhanced over their mainframe equivalents, and their continued use can be ascribed to a number of factors. Firstly, the expense of developing more sophisticated replacement software and the difficulty of recouping the associated expenditure when existing software has been available at minimum or even zero cost. Secondly, a reluctance by utilities and their consultants to adopt and train their staff in the use of new computer programs and, thirdly, the conservative attitude of international lending agencies in promoting the adoption of alternative and, potentially, more advanced methodologies.The latter reason is particularly valid in the case of WASP and the failure of more recently developed, and potentially superior, software packages such as EGEAS and SUPEROLADE to be accepted as preferable or even acceptable alternatives.

The advent of the PC and the relentless advances in computer processor speeds, memory and hard disk storage capacities have transformed the computational capabilities available for analysing water and electricity supply systems. At the same time, the development of powerful Microsoft Windows© based object orientated programming languages can now provide seamless access to graphical user interfaces (GUI's), database creation, population and interrogation, and the graphical presentation of results. More recently, the availability of machine code compilers for languages such as Microsoft's Visual Basic© means that numerically intensive programs can be produced with execution times comparable with those of scientific languages such as FORTRAN. Such advances have enabled the development of new, generalised, user-friendly computer programs which are capable of analysing complex interconnected water and electricity supply systems without needing to resort to previously necessary approximations and simplifications.

Scope of Modelling and Optimisation

As previously indicated, the scope of the HEC-5 and ARSP computer programs is limited to simulating the operation of reservoirs supplying water demands and releases for hydroelectric power generation. This approach probably reflected prevalent conditions in the USA, where the availability of extensive transmission networks effectively ensured that all hydropower generated could in fact be dispatched. However, this is not necessarily the case for generation systems in many other countries, where it is important to model, *via* some form of load dispatch simulation, the integrated operation of hydro, thermal and now wind plants, as well as the effects of regional, diurnal and seasonal electricity demand variations.

In many African and other countries it remains vital to reconcile hydropower requirements with the often conflicting demands associated with the supply of water for domestic, industrial and irrigation purposes. Similarly, from an operational perspective, it is becoming more widely recognised that load dispatch optimisation needs to take account of the constraints imposed by transmission systems, and hence explicitly model multiple electricity demand areas and transmission line losses. In this context, reference should be made to the suite of models for long, medium and short-term operations planning developed by CEPEL at the University of Rio de Janeiro, and used by ONS, the Brazilian System Operator.

WASP, even in the latest Version IV, and its commercial derivative A/S PLAN, remain single electricity demand area models with no modelling of transmission constraints within their load dispatch simulation routines. Where, as in many countries, hydro plants are located at considerable distances from the major load centres this has led to the development and use of alternative expansion planning software such as SUPER, developed by the Organización Latino Americana de Energía (OLADE). For such reasons, SUPEROLADE rather than WASP has now been widely adopted for planning the expansion of electricity supply systems in Latin America.

Analytical Time Steps

Execution time constraints have meant that most analyses using programs such as HEC-5 and ARSP have been conducted using monthly time steps, and hence calendar monthly hydrological inputs. However, it is perhaps not always appreciated how the use of such a relatively long time step may affect the accuracy of the results obtained. Obviously the effects of simulating or optimising the operation of water resource, water supply and hydro-thermal electricity supply systems with a monthly rather than a weekly or daily time step will depend on the nature of the system being analysed and, in particular, the degree of flow regulation afforded by any storage reservoirs. The use of shorter time steps is likely to be particularly crucial when such systems include river abstractions or 'run-of-river' hydro plants, and the use of average monthly flows is likely to result in the amounts of water available for abstraction or the performance of such plants being over-estimated. Other aspects susceptible to inaccuracy when long time steps are used include the modelling of spillway discharges, and hence flood risk estimation, variations in head and release related hydro plant outputs, 'time-of-travel' effects, and 'day-of-week' demand variations.

Bearing in mind that river flow readings are normally recorded at least on a daily basis, and that modern central processors are more than capable of dealing with computational loads some thirty times those associated with the use of a monthly time step, there now seems little justification in not using daily or at least weekly time steps when analysing the performance of water resource and hydro-thermal power systems. At the same time, the availability of large capacity hard disks mean that there is now little impediment to storing the detailed results of such analyses, either in 'flat' files or in a more easily accessible database format.

Modelling Detail

It is now computationally feasible to model separate or interconnected water and electricity supply systems in considerable detail, even when simulating and optimising their operation over many years of hydrological record. For example, reservoirs, water sources, river reaches, flow points, aqueducts, treatment works, pumping stations, water demands, electricity load centres, generation plant and transmission lines can be individually modelled, and hence approximations associated with concepts such as ‘equivalent reservoirs’ avoided. As an example, Figure 1 illustrates the range of system components that can currently be modelled using PWSC’s generalised AQUARIUS software.

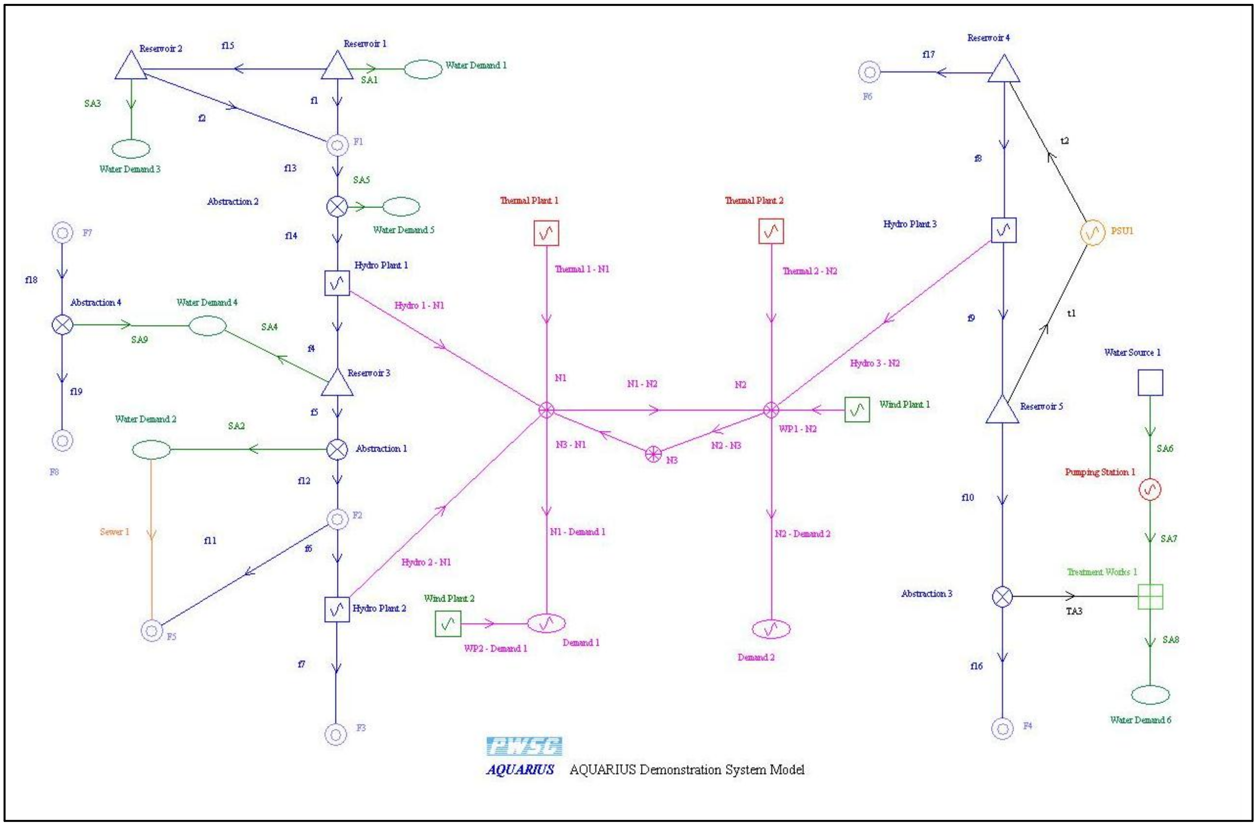

Figure 1 : Water and Electricity Supply System Components Modelled by Program AQUARIUS

The ability to model integrated supply systems in increasing amounts of detail also enables the user to investigate the sensitivity of program results to the scope of the model as well as to the input data. Examples are whether or not transmission line capacities are in fact a constraint in terms of load dispatch optimisation, and the reduction in accuracy associated with use of a weekly rather than a daily simulation time step.

Types of Operating Policy

Even today the operation of many water resource systems is based on the application of individual reservoir rule curves which specify the amount of water to be released, as a function of the quantity of water held in storage and the time of year. In most cases such quantities should be considered as ‘targets’ so as to take account of incremental downstream inflows, and additional rules may be needed to keep the contents of multiple reservoirs ‘in balance’. Recent decades have seen the introduction and optimisation of system-based ‘multiple regime’ rules whereby the operation of alternative sources of water or electricity generation are scheduled as a function of the contents of a sub-set of storage reservoirs and the time of year.

More recently, system operating policies have increasingly been expressed in terms of stored water values and preferably in terms of currency units per volume e.g. US $\$/m^3$. Such policies have two major benefits; firstly, they can be used to define the costs of individual reservoir releases when optimising operation during each simulation time step and, secondly, their equalisation proves to be an effective method of balancing the contents of multiple reservoirs. Stored water values will normally approach zero when a reservoir is full and significant inflows can be expected, and approach the cost ascribed to supply deficits when empty.

Simulation & Optimisation

The difference between simulation and optimisation is often blurred, since simulation programs normally incorporate some form of logic to optimise the allocation of resources within each time step. Such logic needs to be increasingly robust as the systems analysed become more complex, particularly when it is important to take account of transmission constraints, whether these are related to water or electricity supply systems. In such cases the limitations associated with a traditional 'step-by-step' approach to resource/demand allocation, based on a set of user defined 'rules', can rapidly become apparent.

While a number of computer programs purport to optimise the long-term operation of hydro-thermal generation systems, a key criterion in their evaluation is the way in which they model and account for the effects of sustained low flow sequences i.e. historic droughts. While such systems tend, in general, to be energy rather than capacity constrained, the performance of hydro plants during periods of significant reservoir drawdown, and hence reduced generating head, can also be a significant factor when determining supply security. For this reason, many practitioners continue to advocate the combined and integrated use of simulation and optimisation techniques.

Another important criterion is whether a particular methodology explicitly or implicitly relies on the derivation of a 'stationary' or 'non-stationary' long-term operating policy. In this sense, a 'stationary' policy can be defined as one under which an operating decision is made on the basis of, say, the quantity of water held in reservoir storage at that particular time of year. Conversely, a 'non-stationary' policy is one under which the decision would be dependent on a perfect knowledge of future hydrological events. This difference is extremely important since, given the uncertainties associated with hydrological forecasting for any significant period of time, the latter approach will almost certainly result in an over-optimistic estimate of system performance.

Optimisation Methods & Horizons

Just as the then available computing capabilities dictated the scope of analytical models initially developed in the 1960's and 1970's, and the time steps usually employed, they also influenced the choice of optimisation techniques incorporated. For example, while the theory of Linear Programming (LP) and associated solution algorithms were already well established, solution times for problems of any appreciable size remained prohibitive and programs such as HEC-5 and ARSP resorted to faster but less robust network ('out-of-kilter') algorithms for optimising system operation within each simulation time step.

Similarly, programs developed in the 1980's, which called for large numbers of load dispatch optimisations to be performed, often used iterative methods based on a polynomial representation of the load duration curve. Only in recent years has it become feasible to use mathematical programming techniques such as LP to optimise the integrated (daily) operation of complex water resource and electricity supply systems, including the dispatch of generating plant to meet multi-area demands.

It is important to differentiate between optimising long and short-term operation and the implications associated with different optimisation methods. In general terms, long-term operating policy optimisation has the objective of minimising total operating costs over an extended period of, usually historic, records while satisfying specified reliability criteria. Such optimisations can be effected using either a single 'static' system configuration / annual demand combination, or a 'dynamic' expansion plan based scenario where the system configuration and demands vary from year to year. The SDDP (Stochastic Dual Dynamic Programming) software developed and marketed by the Brazilian firm PSR is an example of the latter, with operation being 'optimised' for each of a number of historic or generated multi-year sequences, each equal to the expansion plan period. Obviously the former approach is likely to produce a 'stationary' type operating policy while the latter, which assumes the implementation of a specific development, can be considered to be of the 'non-stationary' variety.

Most long-term operating policy optimisation programs rely on some form of Dynamic Programming (DP). However, unlike LP, the term Dynamic Programming refers to a general approach for solving multi-stage decision problems rather a specific algorithm, and many variations have been proposed and implemented. Whilst, unlike LP, DP is not intrinsically limited to the solution of problems based on linear relationships, it suffers from the 'curse of dimensionality' and many of the proposed algorithms have been developed in order to constrain the amounts of computation involved when analysing complex, 'real life', systems.

In contrast to long-term operating policy optimisation methods, most short-term optimisations are based on forecast demands, hydrological and meteorological values, and component availabilities. Realistic optimisation horizons will normally range from between one day and one week although, in certain cases, a very low likelihood of rainfall may make it realistic to optimise over a longer time horizon. A weekly optimisation horizon may be also be desirable in order to capture week-day and week-end demand variations or, as in the case of countries like Cameroon, necessary to accommodate significant 'times-of-travel' between storage reservoirs and downstream hydropower plants.

Models for short-term optimisation understandably tend to be more detailed than those used for long-term optimisation. For example, the number of load blocks used to optimise the dispatch of generation plant may be increased from the 3 sufficient to reflect peak and minimum loads, to 24 or even 48 per day to model hourly or half-hourly variations. Similarly, such software may be designed to schedule the operation of individual generating units rather than plants, as well as modelling associated transmission systems so as to minimise losses and ensure the supply of reactive power. As a result, non-linear optimisation methods may need to be employed.

Supply Reliability Criteria

For many years system or individual project reliability was expressed in terms of concepts such as 'firm' and 'non-firm' yield for water supplies, and 'firm' and 'non-firm' energy for hydro generated electricity. However, although resulting from analyses of historic flow sequences, the interpretation of such values became increasingly difficult once probabilities of less than 100% were assigned to estimates of 'firm' yield or energy. At the same time it is apparent that the first tranche of 'non-firm' yield or energy will, in fact, have a 'reliability' very close to that ascribed to the 'firm' variety.

When planning the expansion of thermal power systems reliability has conventionally been expressed in terms of Loss of Load Probability (LOLP), and based on the results of probabilistic load dispatch simulations for a given system configuration / demand combination and scheduled and forced outage rates ascribed to generating units. This is the approach incorporated in the WASP expansion planning program, but the suitability of using LOLP and/or un-served energy for assessing the reliability of hydro-thermal supply systems is open to question. For example, in practice, when faced with an unscheduled thermal plant outage the operator of such a system would avoid an immediate supply shortfall by scheduling, if possible, a short-term increase in hydro generation. Once the offending thermal plant or unit was back in service then, as a result of the consequent reservoir drawdown, increased thermal generation would be scheduled in accordance with the long-term system operating policy.

The advent of water and electricity demand driven models now means that system reliability can be evaluated directly in terms of the security with which, for a given system configuration and long-term operating policy, supplies would have been met over a given hydrologic record. In addition, and importantly, it is also possible to model the effect of imposing sets of supply restrictions whereby the demands imposed on a system are reduced by defined amounts in times of abnormally low reservoir contents.

For example, the previously referenced AQUARIUS software allows the user to define different 'drought conditions' in terms of the contents of any sub-set of reservoirs, the imposition of which can be used to reduce 'normal' water and electricity supplies by specific amounts or to modify minimum river flows or reservoir compensation releases. As a result, supply reliabilities can be expressed in terms of the incidence and duration of quantified supply restrictions of specified severity. Such measures of supply security can be more realistic and easier for policy makers to comprehend than concepts of 'firm' and 'non-firm' yield and energy, which are susceptible to interpretation and perhaps misunderstanding. In reality, since many hydro-thermal systems would be unable to meet current levels of demand if there were a recurrence of the most severe historically recorded low flow sequences (droughts), the planned imposition of quantified supply restrictions should form an essential component of any rational and optimised long-term operating policy.

Interpretation and Presentation of Results

As the scope and complexity of modelled systems increase, so does the importance of presenting analytical results in easily digestible form. The advent and widespread application of spreadsheet programs has provided comprehensive facilities for rapidly presenting large amounts of numerical output as graphs and tables, and inbuilt functions enable the user to perform sophisticated statistical analyses and even optimisations, albeit of relatively small sized problems. In consequence, users now expect modern engineering type software to provide similar standards of user friendliness in terms of result presentation or at least enable the output of data to Comma Separated Value (CSV) files for subsequent and easy input to spreadsheet packages.

Even so, interactive forms of result presentation can have an important role to play when demonstrating temporal and geographical variations as well as average values associated with a the results of a particular simulation. Figure 2 illustrates how the program AQUARIUS achieves this by allowing users to construct 'mimic' diagrams which can then be employed to 'play back' simulation results stored in database files.

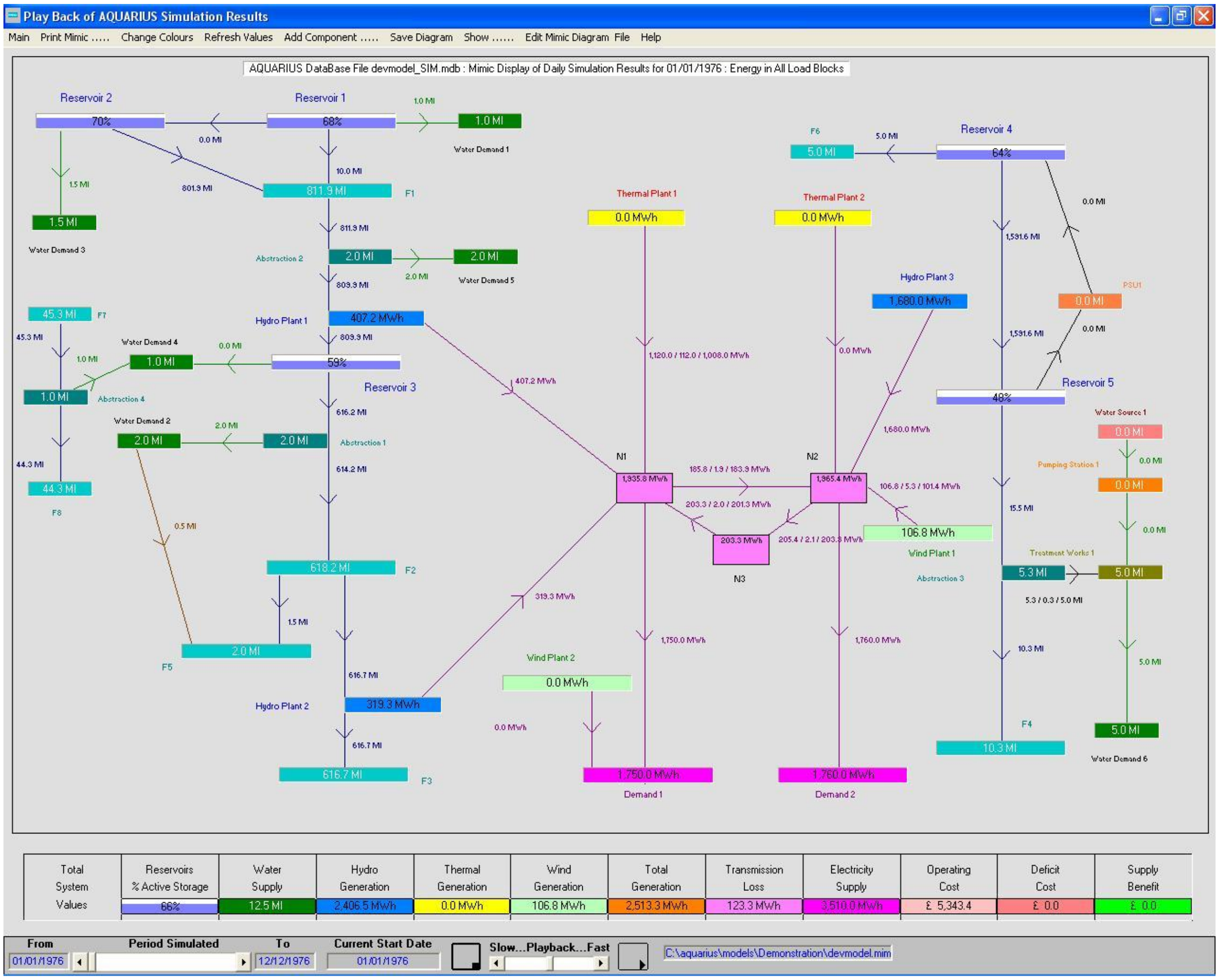

Figure 2 : AQUARIUS Mimic Diagram for Displaying Demonstration System Simulation Results

The ability to 'drill down' into results obtained from analytical software, and hence provide desirable levels of transparency, becomes increasingly important when such programs are used to guide short-term system operation. For example, decisions which determine the load dispatch scheduling of privately-owned generating plant within 'Wholesale Energy Markets' will often have significant financial implications and must be auditable and justifiable.

Such requirements may also dictate the application of robust mathematical programming algorithms rather than previously employed heuristic or rule-based ‘optimisation’ methods.

Modelling of Supply Systems in Africa

The increasingly complex and expansive water and electricity supply systems within Africa provide considerable scope for the application of modern, generalised, computer programs for optimising their operation and development.

As part of the Ethiopian Power System Expansion Master Plan Study, currently being undertaken for the Ethiopian Electric Power Corporation (EEPCO), the AQUARIUS computer program is being used to estimate the power and energy capabilities of potential hydroelectric developments within Ethiopia. This has involved the collection, collation and verification of data relating to some 40 reservoirs and hydro power plants and its incorporation in a model depicted in Figure 3.

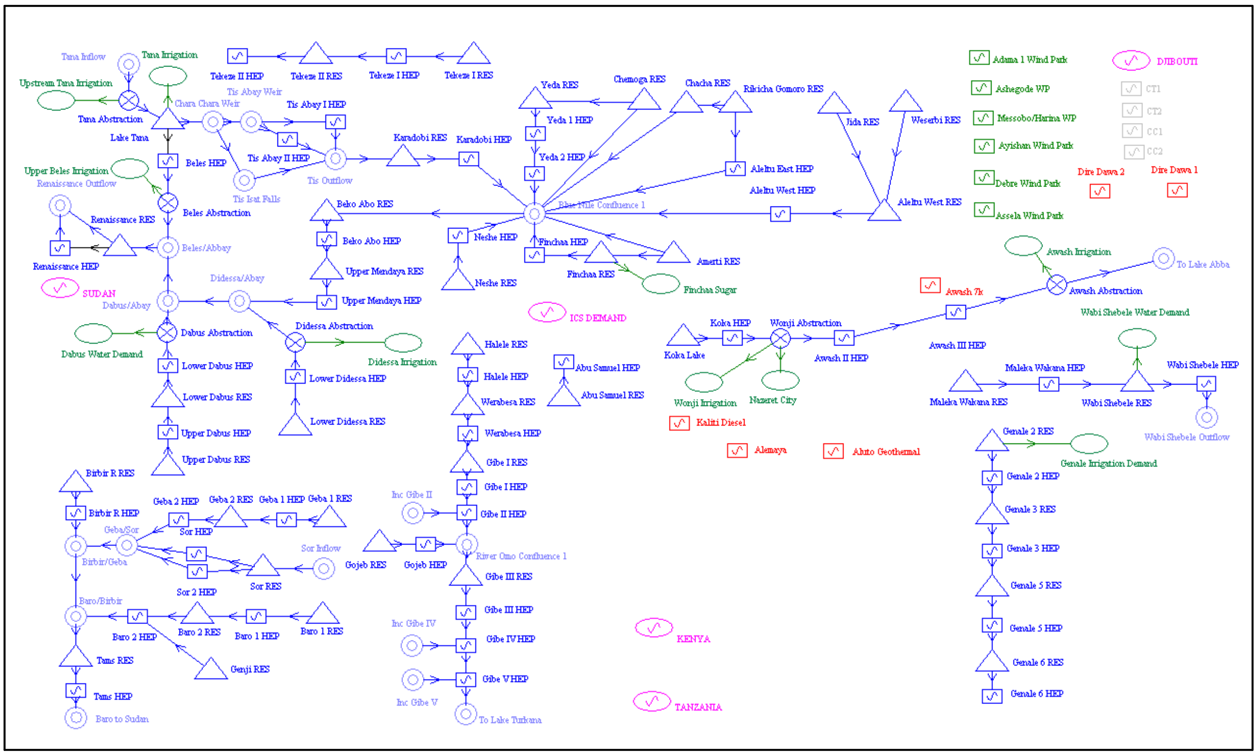

Figure 3 : AQUARIUS Model of Potential Ethiopian Power Generation Projects

The complexity of the model is justified by the need to take adequate account of the cumulative flow regulation effects of reservoir and power plant cascades within each of the seven major river basins, and the capability estimates obtained will form a crucial input to analyses being undertaken to identify the optimal development of the country’s substantial water resources. Existing and potential wind, geothermal, thermal, waste to energy and solar generation plant are also included.

The model employs three load dispatch blocks to represent electricity demands in terms of peak and base loads and total energy, with separate modelling of existing and potential exports. Initial simulations are being carried out using coincident historic flows from 1961 to 1997, but it is planned to extend these time series until 2005. Investigations are also being carried out to identify the sensitivity of simulation results to the time step employed *viz*. daily, weekly or calendar monthly.

The simulation results will be used to determine the capacity and energy availabilities associated with existing and candidate hydroelectric plant as a function of up to five ‘hydrological conditions’, and form a key input to the complementary application of WASP and PWSC’s generation and transmission expansion plan simulator, EPSIM.

The Tanzanian Electric Supply Company (TANESCO) has been using AQUARIUS since 2008 to help guide long-term operation of their hydro-thermal system. Separate models have been constructed to represent system configuration/demand combinations for future years, and the program's 'multi-model' simulation facility used to estimate the probable range and distribution of supply reliability and operating costs for up to three years ahead, based on current reservoir contents and assuming the recurrence of any and all such sequences contained in the historic record. Using a recently developed facility, AQUARIUS is also capable of optimising the operation of such systems for up to a week in advance, for which models such as that shown in Figure 4 can be used.

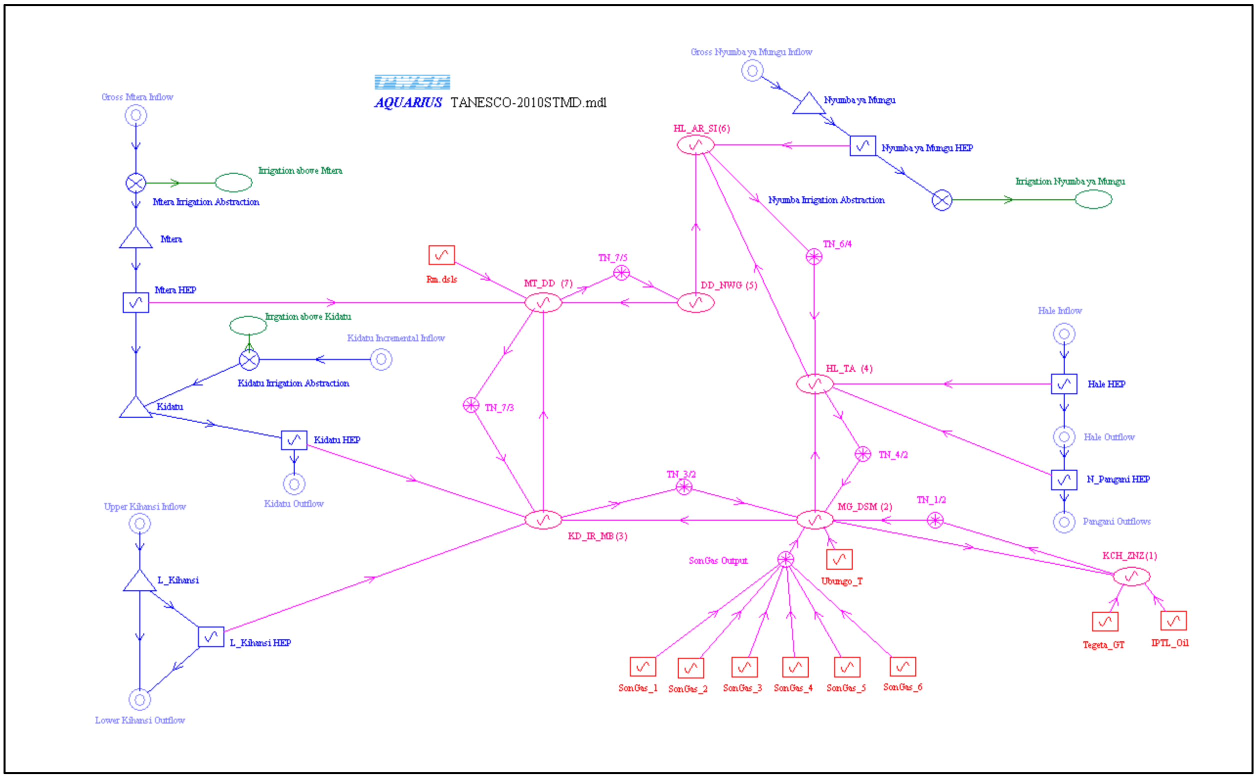

Figure 4 : AQUARIUS Model for Optimising Short-Term Operation of TANESCO's 2010 System

Since the results of such optimisations are designed to be used for detailed load dispatching purposes, the above depicted model employs a 24 block representation of the expected loads in each of seven separate demand centres, together with a basic representation of the associated transmission system so as to account for any major capacity constraints.

Conclusions

Enormous advances in computer capabilities have now made it possible to develop generalised software capable of simulating the performance of complex water and electricity supply systems in great detail and to employ robust mathematical programming techniques to optimise their operation and development. Indeed, it can be argued that the appropriate level of modelling detail is now more likely to be dictated by data availability than by program execution times. When compared with 'main frame' programs developed in the 1960's, 70's and 80's, such software can also demonstrate massive advances in terms of user friendliness and transparency. As African countries increasingly seek to exploit their natural resources, both independently and in unison, it seems desirable that they are fully aware of all the modelling options now available, as well as their strengths and weaknesses.

Daniel Mulatu is Masterplan Study Project Manager, Ethiopian Electric Power Corporation (EEPCO)
Christian Msyani is Manager Grid Operations, Tanzania Electric Supply Company (TANESCO)
Andrew Pearce is Technical Director, Energy Strategic Consulting, Parsons Brinckerhoff, UK
Timothy Wyatt is Director, Power & Water Systems Consultants Ltd., UK (PWSC)