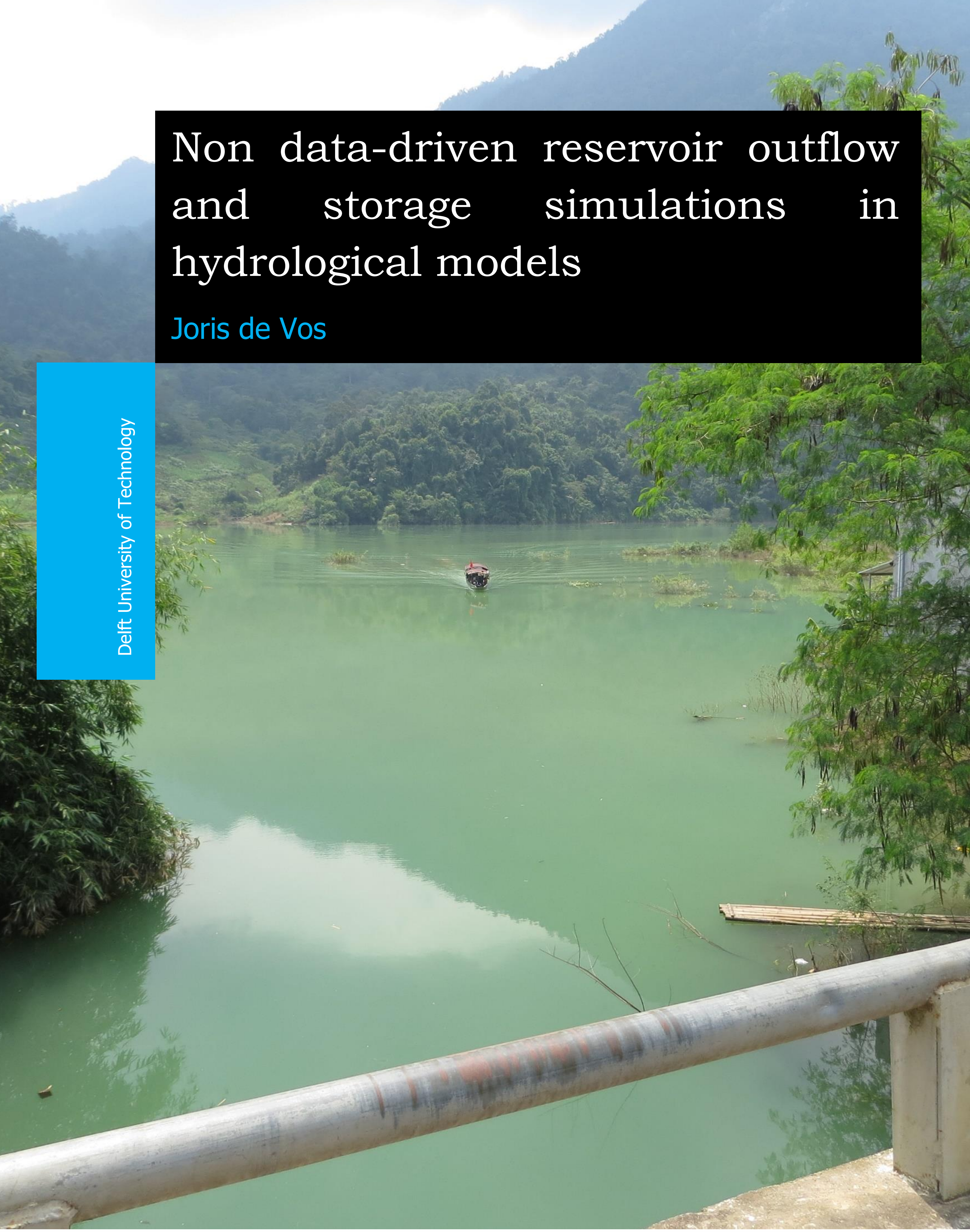
Non data-driven reservoir outflow and storage simulations in hydrological models

Joris de Vos

Delft University of Technology



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Challenge the future

Non data-driven reservoir outflow and storage simulations in hydrological models

By

Joris de Vos

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Supervisor:	Dr. ir. M.M. Rutten	TU Delft
Thesis committee:	Prof. dr. ir. N.C. van de Giesen	TU Delft
	Dr. ir. P. Droogers	FutureWater
	Dr. ir. C.J. Sloff	TU Delft

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Preface

This master thesis report is the final product of my study Civil Engineering, specialization Water Management at Delft University of Technology. It will not only be the last product of my MSc thesis research, it is also a milestone that emphasizes the end of a fulltime educational career that took not less than twenty years. Although twenty years sounds as quite a long time in which many lessons are learnt, I got absolutely convinced from the fact that learning does not stop after achieving a TU Delft diploma.

During my studies I got more aware about the fact that there are too many subjects where I do not know much about and for this reason, collaboration is for me the right procedure for the acquisition of knowledge and thus the key to success. I found out that multidisciplinary work suits me more than thoroughgoing research, however a good fundamental knowledge basis is essential in order to contribute to multidisciplinary projects. I am grateful that I was able to acquire this knowledge at TU Delft.

Now I am talking about collaboration, I need to say that it is not always a matter of course. There are often other interests that impede collaboration, like concerns about data. This became clear during this thesis research, for which not a lot of data was made available. Despite of this, I want to thank the few data suppliers who made my research possible.

I also want to thank my graduation committee, consisting of Martine Rutten, Nick van de Giesen, Peter Droogers and Kees Sloff for taking the time to assess my thesis report. Especially Martine I want to thank for the advice in writing a report about this non-straightforward topic with results that were not always easy to interpret or write about for me.

Further I like to thank all my friends, fellow students and co-board members of the Dispuut Watermanagement for the great times we had during study- and non-study related activities. Though it was doing measurements on the Pampanga River in full sunlight or preparing plates with cookies for the weekly cookie breaks, I enjoyed every second of it!

Last but not least, I like to thank my parents and brother for their unconditional support and trust, during those times when I needed it the most.

I hope you enjoy reading my thesis!

Joris de Vos

Delft, June 2015

Abstract

In the last half century, many dams have been constructed on a global scale to help people get control over water resources. The effects of the reservoirs that are impounded after construction of the dams are that downstream river discharges cannot be classified as natural flows any more. Different water related interests make that many dams are operated in order to contribute to one or more operational goals such as irrigation water supply, hydropower generation and flood control. Data on individual reservoirs are difficult to obtain, especially operational rules and historical time series on inflow, storage and outflow. The consequence is that exact reservoir behaviour is often hard to simulate. Simulation of reservoir operations is important to investigate the effects of climate change and changes in human water demands on water availability in the future. There are multiple reservoir simulation models available that do their own assumptions in order to simplify reservoir outflow and storage simulations in the best possible way.

In this study, a literature review is performed first to find out how several existing hydrological models take into account reservoirs in terms of outflow and storage simulations. Furthermore it is investigated how easy-to-obtain parameters and datasets can contribute to reservoir simulations. The sensitivity and performance of the existing reservoir modules in hydrological models with low data demands are tested for a sample of sixteen reservoirs for which data is available. The time series data of the sixteen reservoirs in combination with a reservoir property named the Impoundment Ratio and a drought index named the Standardized Precipitation Evapotranspiration Index are used to develop a new reservoir simulation model. This newly developed model is also subjected to a sensitivity and performance test. The sample of tested reservoirs includes reservoirs in the USA, Central Asia and Southeast Asia. The sensitivity and performance assessments are based on two goodness of fit parameters, the normalized root-mean-square error (NRMSE) and the coefficient of determination (r^2), and a visual inspection of results.

Overall performance of all tested reservoir simulation models is bad to moderate in terms of NRMSE and r^2. It seems that a target release approach implemented in the Soil and Water Assessment Tool performs generally worst for simulation of both discharge and storage. All other tested models perform better, however it is difficult to observe simulations that are very distinctive in a positive way. A natural lake outflow scheme seems to be the best choice for over-year American reservoirs. Regarding storage simulation it is often a reservoir scheme designed by Hanasaki et al. (2006) or the newly developed reservoir simulation model that shows the best results, since they take into account over-year storage fluctuations. The natural lake outflow scheme and the scheme implemented in the Soil and Water Assessment Tool generally perform worse because they are not designed to simulate over-year fluctuations. For the within-year reservoirs in Central and Southeast Asia, it is often least bad not to model individual reservoirs and use actual inflow as a proxy for outflow. Within-year storage simulation is often best represented by the newly developed reservoir simulation model. Over-year storage fluctuations for two over-year Asian reservoirs are best represented by the newly developed reservoir simulation model or a reservoir scheme designed by Hanasaki et al. (2006).

This study shows that reservoir modules with low data requirements are not always significantly beneficial for the simulation individual reservoirs. The Impoundment Ratio and the Standardized Precipitation Evapotranspiration Index are considered as useful data for the simplification of reservoir operation simulations. For further research, efforts have to be made to retrieve more time series data so that the reservoir modules can be tested for multiple situations. It is also advised to build all

reservoir modules in one hydrological model so that error propagation analyses can be performed for reservoir systems that are connected in series. Finally, further research should be done on worldwide representation of reservoir water demands since it affects the outflow distribution of relatively large reservoirs and many models need water demand as model input.

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List of acronyms

CSIC:	Spanish Scientific Research Council
DEM:	Digital Elevation Model
DVRS:	De Vos Reservoir Scheme
FAO:	Food and Agricultural Organization of the United Nations
GRanD:	Global Reservoir and Dam Database
HIRS:	Hanasaki Irrigation Reservoir Scheme
HNIRS:	Hanasaki No Irrigation Reservoir Scheme
ICOLD:	International Commission on Large Dams
ICWC:	Interstate Commission for Water Coordination of Central Asia
IR:	Impoundment Ratio
JAXA:	Japan Aerospace Exploration Agency
NASA:	National Aeronautics and Space Administration
NLOS:	Natural Lake Outflow Scheme
PDI:	Palmer Drought Index
SPEI:	Standardized Precipitation Evapotranspiration Index
SPI:	Standardized Precipitation Index
TRMM	Tropical Rainfall Measuring Mission
SWAT:	Soil and Water Assessment Tool
WEAP:	Water Evaluation And Planning System
WCD:	World Commission on Dams

1 Introduction

1.1 Background

By the end of the 20th century, there were over 45000 large dams built in the world to help people get control over water resources (ICOLD 1998; WCD 2000). Main purposes of dams are provision of water for irrigated agriculture, domestic use or industrial use, hydropower generation and flood control. The total storage capacity of all the large dams based on dam design is about 6000 km^3 (Lecornu 1998).

Except for the positive control over water resources, dammed reservoirs also cause negative water related aspects to occur. Reservoirs have both impact on ecological and sociological problems as well (WCD 2000). Examples of ecological problems are fragmentation and transformation of aquatic and terrestrial ecosystems and endangerment of fish species with in the worst case complete extinction of fish species. The social problems caused by dam constructions are often caused due to forced displacements of people living close to the new built dam. Entire families encounter social problems by displacements. Furthermore, whole societies are disadvantaged due to the altered access to water resources in the area of influence of reservoirs.

A good example of a country where reservoirs bring benefits to society is Vietnam, where hydropower production accounts for 45 percent of the total energy production in the country and where 85 percent of hydropower potential is being used (Thanh Nien News 2013). In the Red River basin, in the north of Vietnam, several large dams have been built in last decades mainly for hydropower production to accommodate for the increase in energy demand (FAO 2014). Moreover, the same system is also the sole water source for domestic uses and irrigation of almost 750000 ha of rice-based farming in the Red River delta, which is critical to social stability and food security in Vietnam. In a world of modernization and industrialization where higher water demands from several sectors may be expected, allocation of water gets more important. In addition, climate change will lead to more dry periods in many parts of the world, including the northwest of Vietnam (Yusuf & Francisco 2009). This can indicate that making adequate decisions about water distribution becomes an even more important issue than it is already right now.

Above stated information makes clear that efficiency in reservoir operations is already a key aspect in water resources management and is likely to become more important over the years as population grows and climate change will lead to more frequent weather extremes. Needs for improved dam operations are denominated in a variety of studies (e.g. Richter & Thomas 2007; WCD 2000).

Aside from needs to see improved dam operations in the world, several reviews are being made already about methods that describe reservoir optimization procedures and simulation methods (e.g. Labadie 2004; Wurbs 1993; Yeh 1985). Authors mention that there are often significant gaps between theoretical developments and real-world implementations. Reservoir operators consider existing optimal reservoir operation methods as too complicated for practical application (Labadie 2004). Thus, it may be concluded that there are often significant deviations between existing optimal reservoir operation procedures and real-world reservoir operations that have a great influence on the hydrological system behaviour.

Insight in these real-world reservoir operations is often impeded due to the fact that not much data is publicly available. Quantitative information about reservoirs such as actual storage and outflow data are often measured in-situ and are hard to obtain (Gao et al. 2012). Also reservoir properties such as minimum and maximum storages and dam characteristics are often considered as sensitive information. Furthermore, good quality hydrological data about the upstream areas of reservoirs that determines reservoir inflow is not always available. This lack in in-situ data makes it difficult to assess the hydrological effects of reservoir operations.

1.2 Research questions

A lack of data on reservoir operations means that reservoir models cannot always be forced by measurements. Therefore, insight in the behaviour of reservoirs is necessary to come to well informed decisions how reservoirs should be modelled. There have been several studies that have tried to develop models for simulation of reservoirs, all having different data investments. It is to date unknown how well these models work compared to each other and if there are reservoir types for which a particular reservoir simulation model generally works the best or the worst. Further it is interesting to know whether particular data demanded by models may be convenient to retrieve or not. It is also worth investigating if there are particular easy-to-obtain variables that are not yet taken into account by existing reservoir simulation models that may be useful for reservoir simulations. In order to find this all out, the following research question is proposed:

"How can individual reservoir operations be modelled by using a combination of available reservoir simulation models and easy-to-obtain data?"

This research question is supported by the following sub-questions:

1. How do several existing (hydrological) models take reservoir operations into account for several types of reservoirs and how well do they perform and for which data investment?
2. How can different easy-to-obtain datasets and reservoir properties be beneficial for the simulation of reservoir operations?
3. Which types of reservoir simulation models should be applied for which combination(s) of reservoir properties and climatic properties for the area where the reservoir is located in?

Since it is impossible to focus on all reservoirs on the world due to the unavailability of data, it has to be said that this study is only based on a specific sample of reservoirs where proper data is available. Due to this fact, no world covering conclusions will be drawn at the end of this thesis, but there will be essentially recommendations about new insights how to proceed in the science of reservoir modelling.

1.3 Thesis outline

This thesis consists of 9 chapters, of which this is Chapter 1. In Chapter 2, a literature review of existing reservoir routing models is presented. In Chapter 3 it is described which reservoir data is available for this study. Chapter 4 describes a newly proposed reservoir simulation model. Chapter 5 describes the methods how existing reservoir modules will be compared with each other and with the newly proposed reservoir simulation model. The results will be presented in Chapter 6, a discussion can be found in Chapter 7. After this, the conclusion will be drawn and recommendations are given in Chapter 8. Finally a bibliography is presented in Chapter 9.

2 Literature

2.1 Review on reservoir simulation models

Reservoir simulation models try to approximate the actual behaviour of a reservoir system (Yeh 1985). These type of models provide the response of the reservoir system for certain inputs taking into account actual decision rules, with the intention that the decision maker can examine the results of several scenarios on an existing or new reservoir system or that hydrologists can assess the effect of reservoir operations on the hydrological system. Simulation models often include one or more of the following general components:

1. Target release approach: desired water storages are defined for different seasons or even parts of seasons. Reservoirs often have guidelines that specific volumes should be maintained during the year. If these volumes are known to the modeller, in theory a truthful reservoir model could be made.
2. Multiple zoning approach: reservoir simulation models often include the possibility to include various storage zones, like the flood control zone, conservation zone, buffer zone and inactive zone. A discrete descriptive relationship is often given between the reservoir storage and the outflow.
3. Single zoning approach: instead of using multiple zones to simulate reservoir outflows, now only one zone is taken into account. There is often a continuous relationship given between the reservoir storage and the outflow.
4. Inflow dependency approach: reservoir outflow calculation is based on actual inflow and/or averaged inflow over a certain historical time interval.
5. Conditional rule curves: reservoir outflows are dependent on expected natural inflows for some prescribed time period in the future.

In the next sections, several key examples of existing reservoir outflow simulation models found in literature will be described together with their data demand and follow-up research.

2.1.1 Neitsch et al. (2002) (SWAT)

For development of the Soil and Water Assessment Tool (SWAT), Neitsch et al. (2002) used a general reservoir modelling algorithm based on a reservoir target release approach.

SWAT (Neitsch et al. 2002) distinguishes four types of possible reservoir outflow procedures, of which two are fully based on measured reservoir outflows. These two modules model the reservoir outflows based on daily respectively monthly measured outflow values. One can understand that full time series of daily or monthly outflows are not always publicly available. A third reservoir outflow modelling method assumes that the outflow of reservoirs follows the average annual release rate, taking into account the minimum and maximum reservoir storage: if the reservoir storage drops below the minimum storage, no water is released. If the reservoir storage exceeds the maximum storage, all water in excess of the maximum storage volume is released. For this reservoir outflow procedure, minimum and maximum reservoir storage values are necessary as well as the (long term) average release rate:

$$\begin{aligned} Q_{out} &= Q_{out,avg}, if\ S_{min} < S \leq S_{max}\ and \\ Q_{out} &= 0, if\ S \leq S_{min}\ and \\ Q_{out} &= \max\left(S - S_{max}, Q_{out,avg}\right), if\ S > S_{max} \end{aligned} \qquad \text{(eq. 1)}$$

where S_{min} = the minimum reservoir storage (m^3), S_{max} = the maximum reservoir storage (m^3) and $Q_{out,avg}$ = the long term average release rate (m^3/s). S_{max} and S_{min} can be estimated from a combination of satellite images and a DEM.

A fourth reservoir outflow modelling procedure in SWAT works according to a target release approach. This simulation-based approach tries to mimic reservoir rules that are set by reservoir operators, however the method is simplistic and not all decision criteria could be taken into account. The model tries to approximate a certain target volume S_{targ} and this could be a function of soil moisture and flood season. The argumentation is that there is no volume reservation for flood control in the non-flood season, so the reservoir target storages are low in the flood season and high in the non-flood season. S_{targ} is calculated by:

$$S_{targ} = S_{max}\ if\ mon \leq mon_{fld,beg}\ or\ mon\ \geq\ mon_{fld,end} \quad \text{(eq. 2)}$$

where mon = the operational month (-), $mon_{fld,beg}$ = the month corresponding with the begin of the flood season (-) and $mon_{fld,end}$ = the month corresponding with the end of the flood season (-). One should be aware that S_{max} is in this case the maximum target storage value that does not necessarily has to correspond with the actual maximum reservoir storage.

In the flood season, S_{targ} is calculated with the formula:

$$S_{targ} = S_{min} + \frac{\left(1 - \min\left[\frac{SW}{FC}, 1\right]\right)}{2} * (S_{max} - S_{min})\ if\ mon_{fld,beg} < mon < mon_{fld,end} \quad \text{(eq. 3)}$$

where SW = the actual average soil water content in the upstream basin (mm) and FC = the water content of the upstream basin soil at field capacity (mm). One should be aware that S_{max} and S_{min} are in this case again the maximum and minimum target storage values that do not necessarily have to correspond with the actual maximum and minimum reservoir storages.

It is also possible to specify the value for S_{targ} manually. The reservoir outflow per day is calculated with the formula:

$$Q_{out} * 86400 = \frac{S - S_{targ}}{ND_{targ}} \quad \text{(eq. 4)}$$

where Q_{out} * 86400 = the reservoir outflow per day (m^3/d) and ND_{targ} = the number of days necessary for the reservoir to reach S_{targ} (-).

If time series data is available, values for S_{max}, S_{min} and ND_{targ} could be calibrated. However since this is normally not the case for data scarce reservoirs, assumptions have to be done. One should be aware that over-year reservoir simulations cannot be well represented since only two target storage values (for S_{min} and S_{max} respectively) could be defined.

In short, demanded data for this method consists of:

- S_{min}: the minimum reservoir storage (m^3)
- S_{max}: the maximum reservoir storage (m^3)

- $mon_{fld,beg}$: the month corresponding with the begin of the flood season
- $monfld_{,end}$: the month corresponding with the end of the flood season
- ND_{targ}: the number of days necessary for the reservoir to reach S_{targ}
- *SW*: the actual average soil water content in the upstream basin (mm)
- *FC*: the water content of the upstream basin soil at field capacity (mm)
- Q_{in}: time series of reservoir inflow (m^3/s)

Works influenced by Neitsch et al. (2002)

Wu & Chen (2012) took the existing reservoir outflow in SWAT as a starting point to develop an advanced version of a reservoir target release approach. Next to flood control as a reservoir purpose, three other operational reservoir purposes are taken into account in this reservoir routing scheme, namely hydropower generation, downstream water supply and water impoundment (e.g. for navigation). Compared to the original scheme applied by Neitsch et al. (2002), this scheme should be better in representing over-year storage fluctuations. The complete formula for representing reservoir outflow is determined as:

$$Q_{out} = \left\{1 + \alpha \left[\frac{S - S_c}{\max(S_{max} - S_c, S_c - S_{min})} + \beta \frac{Q_{in,30,avg} - Q_{in,30}}{\sigma_{30}} \frac{S - S_{min}}{S_{max} - S_{min}} + \gamma \frac{S - S_{max}}{S_{max} - S_{min}}\right] k(mon)\right\} Q_{out,avg} \quad \text{(eq. 5)}$$

where *α*, *β* and *γ* are dimensionless decision-based parameters that need to be calibrated for every reservoir, *k(mon)* = the ratio of the standard deviation to the mean daily outflow for each calendar month (-), *S* = the actual reservoir volume (m^3), S_c = the critical reservoir volume (m^3), S_{min} = the dead reservoir volume (m^3), S_{max} = the flood control storage volume, $Q_{in,30}$ = the long term (30-day) average inflow before the simulation day and σ_{30} = the standard deviation of long term (30-day) average inflow.

Compared to the target release approach of Neitsch et al. (2002), this reservoir scheme needs more input information such as the reservoir characteristic S_c additional to S_{min} and S_{max}. Furthermore, the observed historical reservoir storage, inflow and outflow for a certain period are required in order to compute *k(mon)*, $O_{out,avg}$, $Q_{in,30}$ and σ_{30} and to calibrate *α*, *β* and *γ*. Given the fact that this data is generally not available for a reservoir, this model scheme can only be applied if historical data is available.

2.1.2 Hanasaki et al. (2006)

Another work that heavily influenced current existing reservoir models is performed by Hanasaki et al. (2006). This model makes use of the inflow dependency approach which is often seen in reservoir simulation models. This simulation-based reservoir routing algorithm makes a distinction between reservoirs for irrigation purposes and reservoirs for non-irrigation purposes. Reservoir operation rules are defined in relation to an operation year, of which the first month is defined as the month that the discharge drops below the mean annual discharge after the longest consecutive period of above mean discharges.

A three step approach was adopted to model reservoir operations. First, inter-annual release fluctuations that are caused by inter-annual inflow variations, are taken into account by defining a release coefficient k_{rls} which is defined as:

$$k_{rls} = S_{begin}/\alpha S_{max} \qquad \text{(eq. 6)}$$

where S_{begin} = the storage at the beginning of the operational year, α = non-dimensional constant (chosen by Hanasaki as 0.85) and S_{max} = the total storage capacity of the reservoir. This coefficient lowers year round releases for $S_{begin} < \alpha S_{max}$ and increases year round releases for $S_{begin} > \alpha S_{max}$.

The second step from this approach is the determination of provisional reservoir release Q'_{out}. In this step, the distinction between irrigation reservoirs and non-irrigation reservoirs is made. For a non-irrigation reservoir, provisional release was defined as constant throughout the entire year. Boundary conditions were set to prevent that the reservoir will overflow or deplete. Provisional release of a non-irrigation reservoir is parameterized as:

$$Q'_{out} = Q_{in,avg} \qquad \text{(eq. 7)}$$

where Q'_{out} = the provisional release (m^3/s) and $Q_{in,avg}$ = the mean inflow (m^3/s). Release of irrigation reservoirs has a somewhat more complex representation that is parameterized as:

$$Q'_{out} = \begin{cases} \frac{Q_{in,avg}}{2} * \left(1 + \frac{\sum_{area}\{k_{alc} * \left(d_{irg} + d_{ind} + d_{dom}\right)\}}{d_{mean}}\right), \left(d_{mean} \geq 0.5 * Q_{in,avg}\right) \\ Q_{in,avg} + \sum_{area}\{k_{alc} * (d_{irg} + d_{ind} + d_{dom})\} - d_{mean}, (d_{mean} < 0.5 * Q_{in,avg}) \end{cases} \qquad \text{(eq. 8)}$$

$$d_{mean} = \sum_{area}\{k_{alc} * \left(d_{irg,avg} + d_{ind,avg} + d_{dom,avg}\right)\} \qquad \text{(eq. 9)}$$

where k_{alc} = a coefficient that corrects for reservoirs if there are more reservoirs upstream (=1 if there are no more reservoirs upstream), d_{irg} = the irrigation water withdrawal (m^3/s), d_{dom} = the domestic water withdrawal (m^3/s), d_{ind} = the industrial water withdrawal (m^3/s) and d_{mean} = the mean annual total water demand (m^3/s). Σ_{area} means integration over the basin downstream of the reservoir, which is limited to a certain distance away from the reservoir, in Hanasaki et al. (2006) defined as 10 grid cells downstream of the reservoir (≈1100 km if grid cells of 1° x 1° are considered). By means of this representation of an irrigation reservoir, it is assumed that reservoir outflow is at least 50% of the mean inflow. Irrigation reservoirs are further distinguished by defining reservoirs with large and small water demand. Large water demand is defined when water demand d_{mean} exceeds 50% of $Q_{in,avg}$, small water demand is defined when water demand d_{mean} does not exceed 50% of $Q_{in,avg}$.

The third step in calculating the reservoir release is combining inter-annual release fluctuations and provisional reservoir releases which were calculated in the previous steps. The relative reservoir size is taken into account as well. Storage fluctuations are restricted to a fluctuation range between a certain S_{max} and S_{min}. The release Q_{out} (m^3/s) is parameterized as:

$$Q_{out} = \begin{cases} k_{rls} * Q'_{out}, (IR \geq 0.5y) \\ (\frac{IR}{0.5})^2 k_{rls} * Q'_{out} + \{1 - (\frac{IR}{0.5})^2\} Q_{in,avg}, (0y \leq IR < 0.5y) \end{cases} \quad \text{(eq. 10)}$$

where *IR* = the impoundment ratio of the reservoir which is defined as $IR = S_{max} / (Q_{in,avg} * 365 * 86400)$. k_{rls} = the release coefficient determined in step 1 and Q'_{out} = the provisional release determined in step 2. If the reservoir is relatively small, the concept is that release is also dependent on inflow to prevent that small reservoirs fill up and empty down too soon.

In short, demanded data for this method consists of:

- S_{min}: the minimum reservoir storage (m^3)
- S_{max}: the maximum reservoir storage (m3)
- *IR*: the impoundment ratio of the reservoir (y)
- α: a constant used for over-year storage simulations (-)
- *d*: water demand time series on a daily/monthly interval (m^3/s)
  - d_{irg}: irrigation water demand (m^3/s)
  - d_{ind}: industrial water demand (m^3/s)
  - d_{dom}: domestic water demand (m^3/s)
- k_{alc}: a coefficient that corrects for reservoirs if there are more reservoirs upstream
- Q_{in}: time series of reservoir inflow (m^3/s)

Works influenced by Hanasaki et al. (2006)

A significant number of studies adopted the algorithm of Hanasaki et al. (2006) in their own studies. In a review paper written by Nazemi & Wheater (2014), several representative studies that used or adapted this method are mentioned together with their host model and routing algorithm. In the first place, the algorithm that was originally proposed for global routing models was extended to global hydrological models (Hanasaki et al. 2008; Hanasaki et al. 2010) and land surface models (Pokhrel et al. 2012), and the representation of water demand was adapted from water withdrawals to consumptive uses.

Many studies also adapted the original scheme of Hanasaki et al. (2006). The above described method is often adjusted at some small points. (Döll et al. 2009) made the reservoir model slightly more complex by considering reservoir gains and losses (i.e. evaporation and precipitation) in addition to only inflows. The reservoir storage was also constrained to the 10% storage limit, which is an estimate for the dead storage of the reservoir that cannot be released. The representation of water demand was also adapted from water withdrawals to consumptive uses.

Biemans et al. (2011) altered the schedule by defining the start of the operational year not as the month when the natural flows dropped below the mean annual discharges but as the month when the regulated flows dropped below the mean annual discharges. This makes especially a difference for reservoirs with many upstream reservoirs which can have a significantly regulated inflow. Furthermore, the provisional release calculations for irrigation reservoirs are adjusted in a way that it only takes irrigation water demand into account while neglecting domestic and industrial extractions. Also the minimum outflow is decreased on average. Instead of 50% of the mean annual inflow, the minimum outflow is defined as 10% of the mean monthly inflow, which makes it possible for the reservoir to better follow the irrigation demand patterns. Further, water demand is represented by consumptive uses corrected with conveyance efficiency factors that vary per country to mimic water withdrawals.

Voisin et al. (2013) investigated the model uncertainties from different implementations of the Hanasaki et al. (2006) reservoir simulation approach for the very reservoir influenced Columbia River basin. The model performance was assessed by changing the reservoir demand priorities (irrigation vs. non-irrigation vs. combined) and predictors (withdrawals vs. consumptive uses and natural vs. regulated inflows) in order to derive reservoir releases. It seemed that for the Columbia River basin, the best performing implementation was the combined reservoir demand priority in combination with the mean annual natural inflows and mean monthly withdrawals as predictors. This research shows that the reservoir scheme by Hanasaki et al. (2006) could be applied based on many possible priority and predictor combinations.

2.1.3 Haddeland et al. (2006)

Another study that significantly influenced the scientific community's vision on reservoir operation simulations is done by Haddeland et al. (2006). It makes use of a target release approach and conditional rules curves. This optimization-based reservoir routing algorithm makes a distinction between reservoirs for four different purposes, namely irrigation, flood control, hydropower and water supply/navigation. Reservoir operation rules are defined on a monthly time scale in relation to an operation year that starts in the month when the discharge drops below the mean annual discharge after the longest consecutive period of above mean discharges. The model itself runs on a daily timescale.

An approach consisting of four steps is followed in this procedure to determine reservoir operations. First, the reservoir storage at the end of an operational year is targeted, that is based on expected downstream demands. This reservoir storage at the end of the operational year will be between 60 and 80 percent of the maximum storage as assumed by Haddeland et al. (2006). The second step is to define the daily minimum release. This one is defined as 7Q10, which is the seven-day consecutive naturalized low flow at the dam location with a repetition time of ten years. After this, the third step is to calculate the daily maximum release which is defined as:

$$Q_{max_i} = \min[(S_{i-1} + Q_{in_i}), (S_{i-1} - S_{targ} + \sum_{day=i}^{365} Q_{in_{day}} - \sum_{day=i+1}^{365} Q_{min} \sum_{day=i}^{365} E_{res_{day}})] \quad \text{(eq. 11)}$$

where S_{i-1} = the reservoir storage at the end of the previous day, S_{targ} = the storage at the end of the current operational year, Q_{in} = the simulated inflow in the reservoir and E_{res} = the reservoir evaporation based on the Penman equation.

The fourth step in the procedure, the most complex one, is to use a search algorithm that is based on optimization of objective functions per reservoir function, where possible reservoir outflows fall in a release range between the defined minimum and maximum releases, see Table 1. By using these objective functions to simulate optimal monthly releases, the minimum deficit during the year and the least difference from the target storage at the end of the year could be found.

Table 1: Objective functions used in the reservoir model developed by Haddeland et al. (2006)

Reservoir purpose	Objective function
Irrigation	$$min \sum_{i=1}^{365} (d_{irg_i} - Q_{out_i}), d_{irg} > Q_{out}$$ (eq. 12)
Flood control	$$min \sum_{i=1}^{365} (Q_{out_i} - Q_{flood})^2, Q_{out} > Q_{flood}$$ (eq. 13)
Hydropower	$$min \sum_{i=1}^{365} \frac{1}{Q_{out_i *} \rho * \eta * h * g}$$ (eq. 14)
Water supply, navigation	$$min \sum_{i=1}^{365} (Q_{out_i} - Q_{out,avg})$$ (eq. 15)

where d_{irg} = the forecasted water demand (m^3/s) (not further than 250 km away (≈10 downstream grid cells of 0.5° x 0.5°) and weighed if a demand cell is fed by multiple reservoirs), Q_{out}= the reservoir outflow (m^3/s), Q_{flood} = the bank full discharge (m^3/s), $Q_{out,avg}$ = the mean annual discharge (m^3/s), ρ = the water density (kg/m^3), η = the efficiency of hydropower generation (-), h = the hydrostatic pressure head in reservoir with respect to the downstream level (m) and g = the constant of gravity (m/s^2).

For a complete detailed overview of all the data demand of this model, see Haddeland et al. (2006).

Works influenced by Haddeland et al. (2006)

Numerous authors adopted the reservoir simulation method defined by Haddeland et al. (2006). Nazemi & Wheater (2014) reviewed several studies that used or adapted this method together with their host model and routing algorithm.

Adam et al. (2007) used the reservoir outflow algorithm for application in multiple North Asian river basins. Originally proposed procedures where changed due to the fact that more information was available for the author in the case study area. Minimum discharge was defined as the mean observed winter discharges if enough observations were available. Hereafter, the storage-area-depth relations are changed according to the theory of Liebe et al. (2005), in order to give a better representation of reservoir area for evaporation calculations and head indications for hydropower calculations. Also minimum storages were defined as dead storages of reservoirs. Finally, the hydropower objective function was adapted for monthly price fluctuations during the year.

On a global scale, the reservoir outflow algorithm is applied in the PCRGLOB-WB model (Van Beek et al. 2011). In relation to the algorithm of Haddeland et al. (2006), the model complexity is decreased. First, the expected inflow for each month is prospectively defined as a function of inflows in the same month of the previous years instead of using prognostic flow forecasts. Furthermore the dimensionality of the search for optimized objective functions is limited to two times per year instead of twelve times per year. For the results of objective functions for the other ten months, it is assumed that these could be interpolated between the two optimized objective functions.

2.1.4 Other reservoir outflow models

Wisser et al. (2010)

Wisser et al. (2010) use a simple relationship of reservoir inflow Q_{in} (m^3/s) and mean reservoir inflow $Q_{in,avg}$ (m^3/s) to determine reservoir outflow Q_{out} (m^3/s) in a global hydrological model. This model can be categorized as a model that makes use of an inflow dependency approach. This relationship is represented as:

$$Q_{out} = \begin{cases} \kappa Q_{in} & Q_{in} \geq Q_{in,avg} \\ \lambda Q_{in} + \left(Q_{in,avg} - Q_{in}\right) & Q_{in} < Q_{in,avg} \end{cases} \qquad \text{(eq. 16)}$$

where κ (set to 0.16) and λ (set to 0.6) are constants that are empirically determined by using operational reservoir data of 30 reservoirs globally. This reservoir scheme does not take into account any reservoir property, so every reservoir will be treated the same.

In short, demanded data for this method consists of:

- Q_{in}: time series of reservoir inflow (m^3/s)

Yates et al. 2005 (WEAP)

The “Water Evaluation And Planning” system WEAP (Yates et al. 2005), contains something that looks like a reservoir simulation model, however it is up to the user to define reservoir operational rules. It makes use of a multiple zoning approach. A reservoir should be divided in four zones, see Figure 1: a flood control zone, a conservation zone, a buffer zone and an inactive zone. The reservoir releases water according to the operational rules if the water level is in the conservation zone. If the water level gets above the conservation zone, all water is released in order to keep the flood control zone vacant. If the water level gets in the buffer zone, water is spilled according to the predefined operational rules, however it is multiplied with a factor between 0 and 1 to conserve the dwindling supplies of the reservoir. In exceptional cases, when the water level drops as low as the inactive zone, no water is released since it is considered that there is only dead storage in the reservoir.

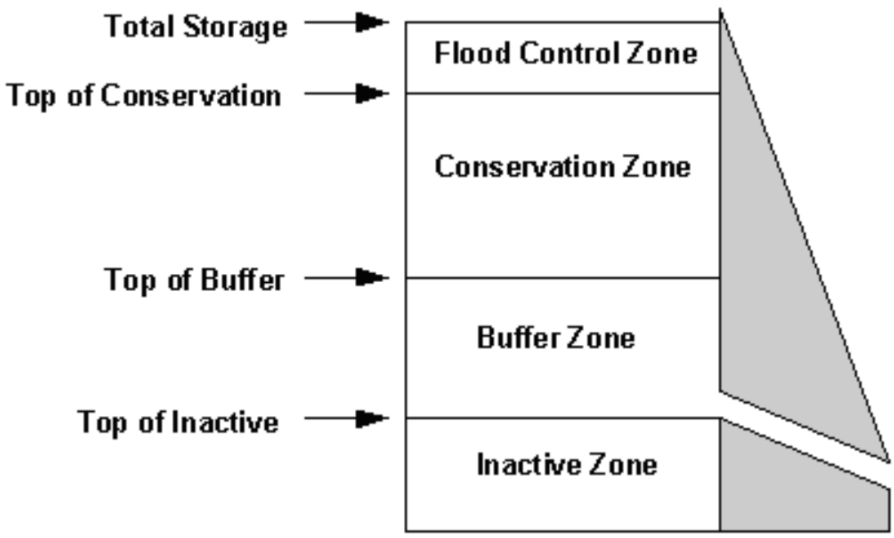

Figure 1: representation of a reservoir in WEAP with four different storage zones

In short, demanded data for this method consists of:

- S_{min}: the minimum reservoir storage = storage of inactive zone (m^3)
- S_{buf}: the storage equal to the capacity of the buffer zone (m^3)
- S_{con}: the storage equal to the capacity of the conservation zone (m^3)
- S_{flc}: the storage equal to the capacity of the flood control zone
- Q_{in}: time series of reservoir inflow (m^3/s)

Döll et al. (2003)

An approach where global reservoirs are simulated like global lakes is described by Döll et al. (2003), and partially by Meigh et al. (1999). This model makes use of a single zoning approach which can be seen in reservoir simulation models. The reason for the representation as a lake is that reservoir management data is considered as essential in order to simulate reservoirs, and often not available. Considering a reservoir like a global lake should give an acceptable representation of a reservoir. Natural lake outflow is dependent on the actual storage of a reservoir. Reservoir (lake) outflow is represented as:

$$Q_{out} = k_r(S - S_{min})\left(\frac{S - S_{min}}{S_{max} - S_{min}}\right)^{1.5} \qquad \text{(eq. 17)}$$

where k_r = a release coefficient (0.01/86400 s^{-1} as defined by Döll et al. (2003)), S is the actual reservoir storage, S_{min} is the minimum reservoir storage (m^3) and S_{max} is the maximum reservoir storage (m^3).

In short, demanded data for this method consists of:

- S_{min}: the minimum reservoir storage (m^3)
- S_{max}: the maximum reservoir storage (m^3)
- k_r: a release coefficient (-)
- Q_{in}: time series of reservoir inflow (m^3/s)

HEC-ResSim

The Reservoir System Simulation (HEC-ResSim) software is developed to model reservoir operations at one or more reservoirs for multiple operational goals and constraints (Klipsch & Hurst 2013). Diverse rule types can be applied so that a reservoir is modelled according to the wishes of the user. There is no default routing module that is applicable for every reservoir if hardly any information about the reservoir is available. This means that this model is only applicable to reservoirs where data is easily available.

For a complete detailed overview of all the data demand of this model, see Klipsch & Hurst 2013.

2.2 Review on the benefits of easy-to-obtain reservoir parameters and datasets for reservoir discharge and storage simulations

There are some easy-to-obtain reservoir parameters and datasets that may be useful in the study of reservoir operation simulations. In this section, the usefulness of one reservoir parameter and one dataset for the simulation of reservoirs will be reviewed upon.

2.2.1 Benefits of impoundment ratio

According to Vogel et al. (1999), the impact of reservoirs on downstream hydrologic conditions will depend partially upon their impoundment ratio IR and yield ratio YR. IR is defined as the ratio between effective reservoir storage and mean annual inflow and YR as the ratio between annual yield and mean annual inflow. Annual yield is defined as reservoir outflow that is beneficially used for e.g. irrigation or hydropower production. Reservoir spills, whether controlled or uncontrolled, do not count as reservoir yield. These spills are defined as instream flow. Another parameter is the so called coefficient of variation on annual inflow C_v, which is defined as the ratio between the standard deviation of annual inflow σ and the mean of annual inflow μ. Hanasaki et al. (2006) also took the impoundment ratio into account in order to simulate reservoirs, without going too deep in theoretical details. Vogel & Stedinger (1987) developed generalized storage-reliability-yield relations and Vogel et al. (2007) derived theoretical relations between C_v, IR and YR from this, see Figure 2. It can be seen that a small impoundment ratio leads to a relatively low yield ratio, meaning that a small part of the reservoir outflow will be efficiently used. If the impoundment ratio rises, it means that the yield ratio rises as well indicating that a bigger part of the reservoir outflow is beneficially released for a certain reservoir purpose. Furthermore it seems that reservoirs with a low C_v value generally show higher yield ratios than reservoirs with a high C_v ratio. Low C_v ratios roughly correspond to reservoirs located in a temperate region, so reservoir inflow is not subject to strong inter-annual changes. High C_v ratios roughly correspond to reservoirs which are located in relatively arid areas, where reservoir inflow is more probably subject to strong inter-annual changes. It seems that those relations provide a good approximation to the overall behaviour of reservoir systems in the USA. From the relations described above it can be concluded that relatively small reservoirs (in terms of impoundment ratio) tend to spill more water than large reservoirs. It is not hard to imagine that during wet seasons, small reservoirs tend to spill relatively more water than large reservoirs do. For example, it is more likely that small reservoirs fill up completely after a storm than large reservoirs do. The water that enters a reservoir after a storm cannot be stored anymore and should go somewhere and so it is spilled. Large reservoirs have more buffer capacity to account for high inflow periods. For this reason, it may be expected that small reservoirs tend to release more water in times of high inflow than large reservoirs do. On this way small reservoirs become more supply driven than large reservoirs. Due to their large buffer capacity, large reservoirs become more demand driven. This results in higher yields for the reservoir.

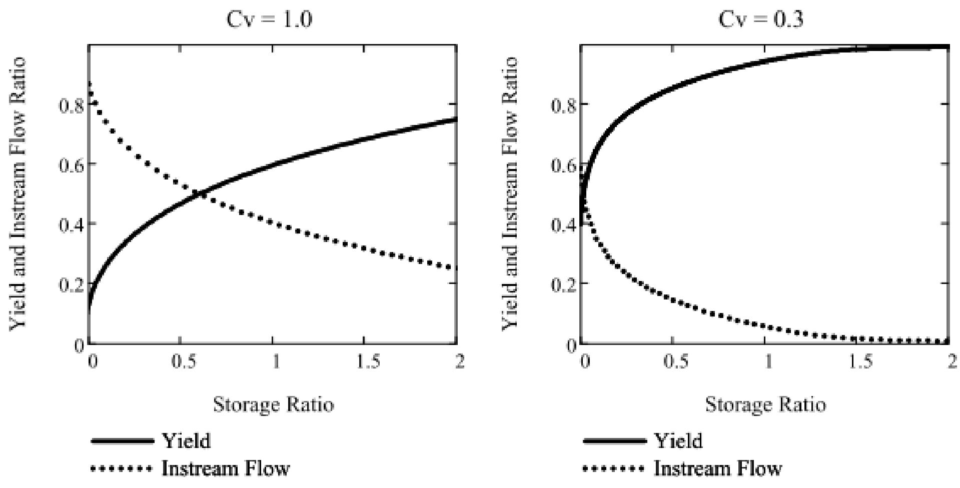

Figure 2: the relationship between the impoundment ratio (Storage Ratio), yield ratio and instream flow ratio for high and low coefficients of variation (Vogel et al. 2007)

2.2.2 Benefits of drought indices

Reservoirs generally tend to fill up during wet periods and empty again during dry periods, however there are big differences in durations of dry periods. Typically there are yearly recurring dry and wet seasons, however dry spells and wet periods can also take for multiple years. Therefore, the filling and emptying frequencies of reservoirs can vary a lot.

It may be useful to take drought parameters into account in order to say something about the filling and emptying processes of reservoir. There are several climate indices that tend to give an estimation of the level of drought at a certain place in a certain moment of time. Generally these indices give an indication how much precipitation has fallen in a certain period of time. Sometimes other drought related variables such as temperature are taken into account. Observed values are compared with historically established norms for one specific area. This means for example that dry dessert areas have the same probability to experience a dry period as a wet rain forest, independent of their relative moisture conditions. The drought indices discussed are the Palmer Drought Index (PDI), the Standardized Precipitation Index (SPI) and the Standardized Precipitation Evapotranspiration Index (SPEI). Compared to the method of Hanasaki et al. (2006) that only takes into account the storage at the end of last operational year, looking at longer term climatic conditions should give more information about possible over-year filling and emptying processes of reservoirs. A reservoir model that contains an over-year storage simulation model helps to give more representative representations of water availability to use as input in hydrological and water resources models.

The Palmer Drought Index (PDI) is designed as an indicator of drought severity (Palmer 1965; Guttman 1998), in order to quantify meteorological drought. It works typically on a monthly basis, however other time intervals are also possible. Before one could give an indication if a month is dry or wet, one needs to come up with climatically appropriate precipitation for every month in a year, which is dependent on normal evapotranspiration, normal recharge, normal runoff and normal loss. This is calculated by taking a long series of years of monthly climatic observations. After this, observed rainfall data for a specific month in time is compared with the applicable monthly climatically appropriate precipitation to define a monthly moisture anomaly. After this, the monthly moisture anomaly is multiplied with a standardization factor to account for variations between different climatic zones. This product for month t is defined as the moisture anomaly index Z_t. After this, the PDI for month t is defined as:

$$PDI = 0.897 PDI_{t-1} + 0.333 Z_t \qquad \text{(eq. 18)}$$

The factors 0.897 and 0.333 are empirically determined by saying that a PDI value of -4 is defined as an extreme drought. This formula shows that the PDI contains a long term memory of previous moisture conditions and takes into account the current moisture anomaly for a fixed portion. This calculation indicates that the PDI is a practical complex drought index and not flexible to account for different drought time scales.

Three types of drought ranked by duration of the event from short to long are meteorological, agricultural and hydrological drought respectively (Keyantash & Dracup 2002). A drought is already defined as a meteorological drought when a deficiency spans an extended period of time. It is not defined how long this time period should be, so if it is dry for a week then it could be classified as a meteorological drought already. Human or societal aspects do not need to be necessarily influenced by a meteorological drought. This changes when the concept agricultural drought is introduced, which is more commonly defined as the availability of water to crops. However, next to precipitation other parameters are important as well as the slope of the soil and the water-holding capacity of the soil. A hydrological drought takes place if the existence of surface and subsurface water supplies in aquifers, streams, lakes and reservoirs decreases. As for agricultural droughts, this is not only dependent on precipitation amounts but also on other (human introduced) variables that influence the hydrological system like irrigation, flood control and hydropower production. Moreover, significant time lags between the departure of precipitation and appearance of hydrological droughts exist.

The Standardized Precipitation Index (SPI) is designed to take into account the time scale over which precipitation deficits accumulate (Mckee et al. 1993; Guttman 1998), which is a pitfall of the PDI. The underlying idea is that droughts take place on different time scales and every time scale has its effects on hydrological variables, as described above. The SPI is calculated over a prolonged precipitation record (preferably at least 30 years), for a specific region. Drought time scales that are interesting for the water analyst could be chosen beforehand. With these time scales, moving total time series could be constructed from the observed (monthly) precipitation data and are used for the SPI computation hereafter. If the water analyst is interested in the six-month events, the monthly time series for the first six months (1-6) and summed and divided by six, after which the first seven months minus the first month (2-7) are summed and divided by six, after which the first eight months minus the first two months (3-8) are summed and divided by six, and so on. On this way, moving average precipitation time series are obtained.

In order to calculate the SPI value, first a probability density function needs to be determined that describes the long-term series of observations. After this, the cumulative probability of the observed precipitation amount is computed. Hereafter the inverse normal function is applied to the probability. This is the SPI. The SPI calculated over a certain time period consists of a series of positive and negative values with an average of zero. If the SPI value is positive, it indicates wet conditions for the applied SPI time scale. On the other hand, negative SPI values indicate dry conditions for the applied SPI time scale.

The usefulness of the SPI as a proxy for hydrological drought is empirically shown by (Vicente-Serrano & López-Moreno 2005). For a river basin in the central Spanish Pyrenees, the SPI at different time scales is compared with surface hydrological variables (river discharge and reservoir storage). It seemed that robust relationships could be found after analysing the role of time scales of the SPI on the river discharges and reservoir storages. Standardized monthly river discharges in this specific river basin (Aragon River Basin) could be well correlated with the SPI at time scales between 1 and 3 months. Standardized monthly reservoir storages could be well correlated with the SPI if this had a time scale between 7 and 10 months. For shorter time scales, it seemed that there was no good correlation between reservoir storages and SPI. This indicates that this specific reservoir is not sensitive to short wet/dry periods. In order to affect the reservoir storage by a drought, these should be of longer duration. It is important to consider that the characteristics of the reservoir (i.e. impoundment ratio), the type of water demand (i.e. irrigation, hydropower) and the local operational rules have an effect on the relation between the stored water and the optimal SPI time scale. It also seemed that particular months are better correlated to the SPI than other months, which means that there is a seasonality in the usefulness to monitor hydrological droughts. For reservoir storages, SPI shows better correlation in autumn and winter than in summer in this case.

A variety on the Standardized Precipitation Index is the Standardized Precipitation Evapotranspiration Index (SPEI) (Vicente-Serrano et al. 2010). The biggest addition to the SPI is the inclusion of temperature in determining the drought. The concept of it is that higher temperatures cause higher evapotranspiration rates. An estimation of potential evaporation ET_p per month is calculated by using the Thornthwaite equation (Thornthwaite 1948):

$$ET_p = 1.6\frac{L}{12}\frac{N}{30}\frac{10T_a}{I}^{\propto} \qquad \text{(eq. 19)}$$

where L is the average day length in hours of the respective month, N is the number of days of the respective month, T_a is the average daily temperature of the respective month, $\propto = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.792 * 10^{-2})I + 0.49239$, $I = \sum_{i=1}^{12}(\frac{T_{ai}}{5})^{1.514}$ a heat index depending on the 12 monthly mean temperatures T_{ai}.

Under global warming conditions, it is determined that rising temperatures have to be included in drought assessments. Mathematically, the SPEI is similar to the SPI and it has the same benefits as the SPI compared to the PDI. For the exact mathematical reproduction, a reference is made to the explanatory paper by Vicente-Serrano et al. (2010).

The usefulness of the SPEI as a proxy for hydrological drought as a supplement to the SPI is shown by Lorenzo-Lacruz et al. (2010). For a river basin on the Iberian Peninsula (Tagus river basin), the SPI and the SPEI at different time scales are compared with surface hydrological variables (river discharge upstream reservoir, reservoir storage and river discharge downstream reservoir). The same results were obtained as performed by Vicente-Serrano & López-Moreno (2005). Standardized monthly reservoir inflows are well correlated with the SPI as well as SPEI at short time scales (4-12 months). Standardized monthly reservoir storages and reservoir outflow are well correlated with the SPI and SPEI at longer time scales (33 months and 48+ months respectively, the longest time scale taken into account is 48 months). This indicates that reservoir storage is not sensitive to short dry/wet periods. Also reservoir outflow does not seem sensitive for short-term fluctuations in wetness. If the performance of SPI and SPEI were compared, it seems that SPEI shows slightly better correlations than SPI for this particular reservoir. The suggested reason for this is that reservoirs are subject to evaporation processes, which indicates that a drought index that combines both precipitation and evapotranspiration processes such as the SPEI is more appropriate for analysis of the response of reservoir storage than an index that only takes into account precipitation such as the SPI.

3 Reservoir data

This chapter briefly describes the reservoir data that is used in this study. After an overview of the locations of the reservoirs over the world is given, more detailed overviews of the three specific geographic locations where data is available are given: United States of America, Central Asia and Southeast Asia respectively. Figure 3 shows the locations of 16 reservoirs with available data spread over the world. Retrieved data consists of reservoir properties and time series data. Reservoir properties retrieved are the minimum storage and maximum storage. Time series retrieved are inflow, outflow and storage time series. Actual inflow is used as model input. Long term averaged inflow values are used to calculate the impoundment ratio together with the minimum and maximum reservoir storage. Storage and outflow time series are used for validation purposes.

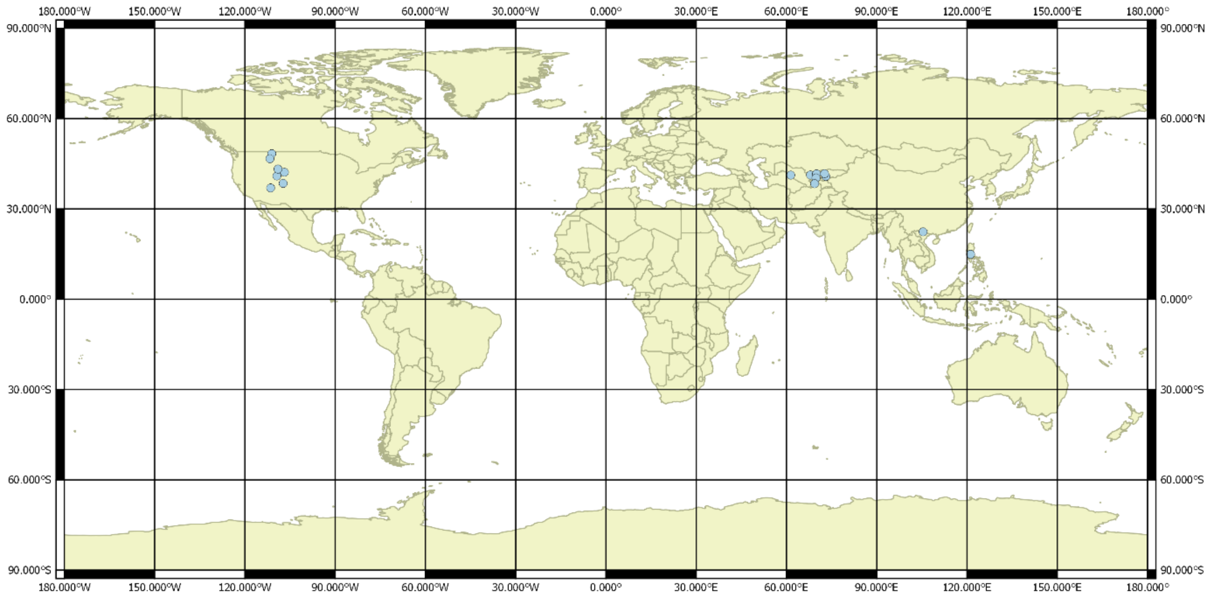

Figure 3: geographic locations of reservoirs with available data on global scale

3.1 United States of America

Data on reservoirs is generally very hard to obtain for third parties. There are only few areas in the world with an open data policy regarding reservoir data. One country that actively shares data about many reservoirs is the United States of America. The organization that is responsible for the acquisition of the data is the United States Bureau of Reclamation (USBR). There are at least two regions in the USA where data could be retrieved from: the Great Plains (GP) region and the Upper Colorado (UC) region. Time series data as well as additional data on reservoir properties are retrieved from http://www.usbr.gov/gp/lakes_reservoirs/, http://www.usbr.gov/uc/crsp/GetSiteInfo and the GRanD database (Lehner et al. 2011). In Table 2, an overview of the retrieved data is presented for seven reservoirs in both regions. The geographical locations together with major rivers are presented in Figure 4. It could be observed that reservoirs have impoundment ratios that approach or exceed unity, which indicates that these reservoirs could have a tendency to show over-year reservoir behaviour. The reservoirs could be mainly classified as multi-purpose reservoirs, with a focus on the combination hydropower and irrigation.

Table 2: retrieved data on reservoirs in the USA

Reservoir name	Region	River basin name	Total storage (Mm^3)	Effective storage (Mm^3)	Mean annual inflow (Mm^3/y)	Impoundment ratio (y)	Time series retrieved (y)
Bull Lake Reservoir	GP	Missouri	188.06	187.16	206.83	0.90	2001-2013
Seminoe reservoir	GP	Missouri	1254.79	1254.10	1114.71	1.13	1951-2013
Canyon Ferry lake	GP	Missouri	2458.33	2457.02	3808.76	0.65	2001-2013
Lake Elwell	GP	Missouri	1687.60	975.11	576.89	1.69	2001-2013
Lake Powell	UC	Colorado	26200.00	24300.00	12982.26	1.87	1964-2013
Blue Mesa reservoir	UC	Colorado	1160.30	1023.00	1157.28	0.88	1969-2013
Flaming Gorge reservoir	UC	Colorado	4673.50	4311.02	1842.13	2.34	1972-2013

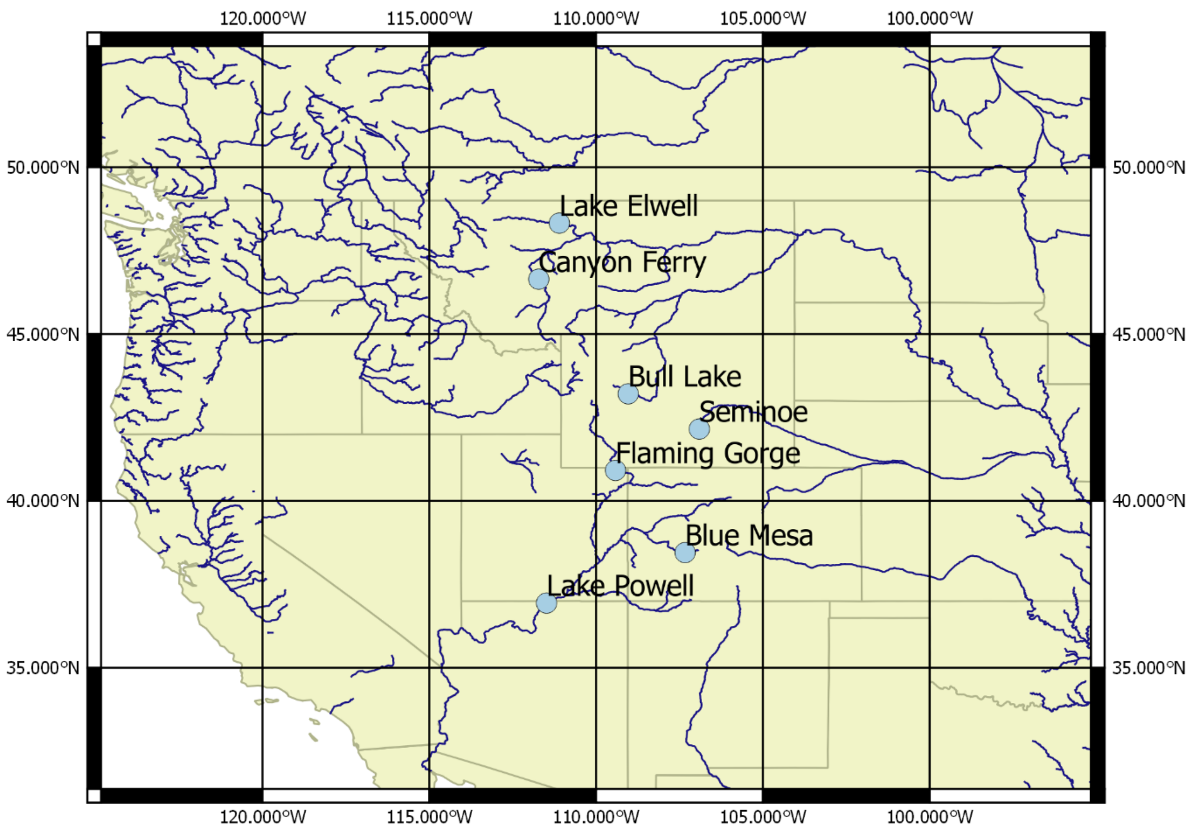

Figure 4: geographic locations of reservoirs in the USA together with major rivers

3.2 Central Asia

Data on reservoirs in Central Asia is the same that is used in a study by Lutz et al. (2012). The time series dataset is then retrieved via personal communication with the authors. Additional data on reservoir properties is retrieved from the website of the Interstate Commission for Water Coordination of Central Asia (ICWC), see http://www.icwc-aral.uz/bwosyr.htm. The reservoirs are located in countries that form Central Asia: Kyrgyzstan (KG), Tajikistan (TJ), Uzbekistan (UZ), Turkmenistan (TM) and Kazakhstan (KZ). In Table 3, an overview of the retrieved data is presented for seven reservoirs. The geographical locations together with major rivers are presented in Figure 5.

Table 3: retrieved data on reservoirs in Central Asia

Reservoir name	Country	River basin name	Total storage (Mm^3)	Effective storage (Mm^3)	Mean annual inflow (Mm^3/y)	Impoundment ratio (y)	Time series retrieved (y)
Toktogul reservoir	KG	Syr Darya	19500.00	14000.00	14027.62	1.00	2001-2010
Andizhan reservoir	UZ/KG	Syr Darya	1900.00	1750.00	4201.49	0.42	2001-2010
Kayrakkum reservoir	TJ	Syr Darya	4030.00	2550.00	20707.77	0.12	2001-2010
Charvak reservoir	UZ	Syr Darya	2050.00	1600.00	7064.76	0.23	2001-2010
Chardara reservoir	KZ	Syr Darya	5400.00	4400.00	20040.34	0.22	2001-2010
Nurek reservoir	TJ	Amu Darya	10500.00	4500.00	25036.25	0.18	2001-2010
Tyuyamuyn reservoir	UZ/TM	Amu Darya	7800.00	5300.00	30726.05	0.17	2001-2010

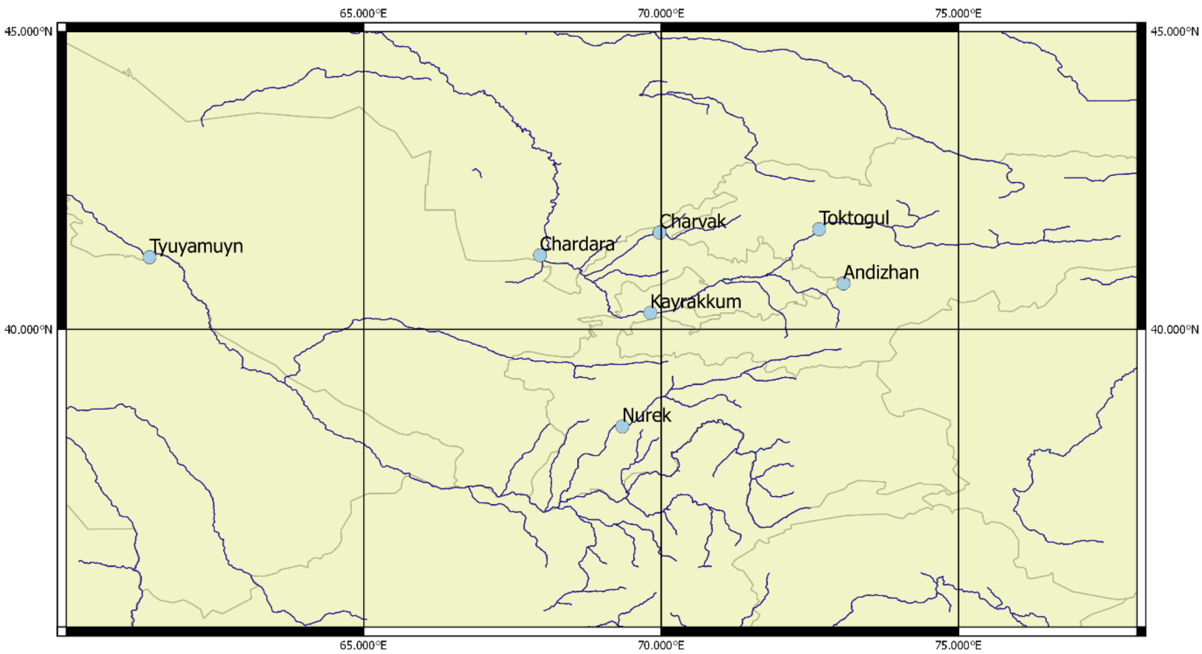

Figure 5: geographic locations of reservoirs in Central Asia together with major rivers

3.3 Southeast Asia

For two reservoirs in Southeast Asia, reservoir data is retrieved. One reservoir is located in Vietnam (Tuyen Quang reservoir) and the other one is located in the Philippines (Angat reservoir). Time series data and data on reservoir properties from Tuyen Quang reservoir are supplied through personal communication by Tran Kim Chau and Hoang Nguyen Son from the Water Resources University in Vietnam (VN). Time series data and data on reservoir properties from Angat reservoir are supplied through personal communication by Russel Rigor from the National Power Corporation in the Philippines (PH). In Table 4, an overview of the retrieved data is presented for two reservoirs. The geographical locations together with major rivers are presented in Figure 6.

Table 4: retrieved data on reservoirs in Southeast Asia

Reservoir name	Country	River basin name	Total storage (Mm^3)	Effective storage (Mm^3)	Mean annual inflow (Mm^3/y)	Impoundment ratio (y)	Time series retrieved (y)
Tuyen Quang reservoir	VN	Red River (Lô River)	2260.00	1699.00	9721.16	0.17	2007-2011
Angat reservoir	PH	Angat River	1077.00	850.00	2354.74	0.36	2009-2013

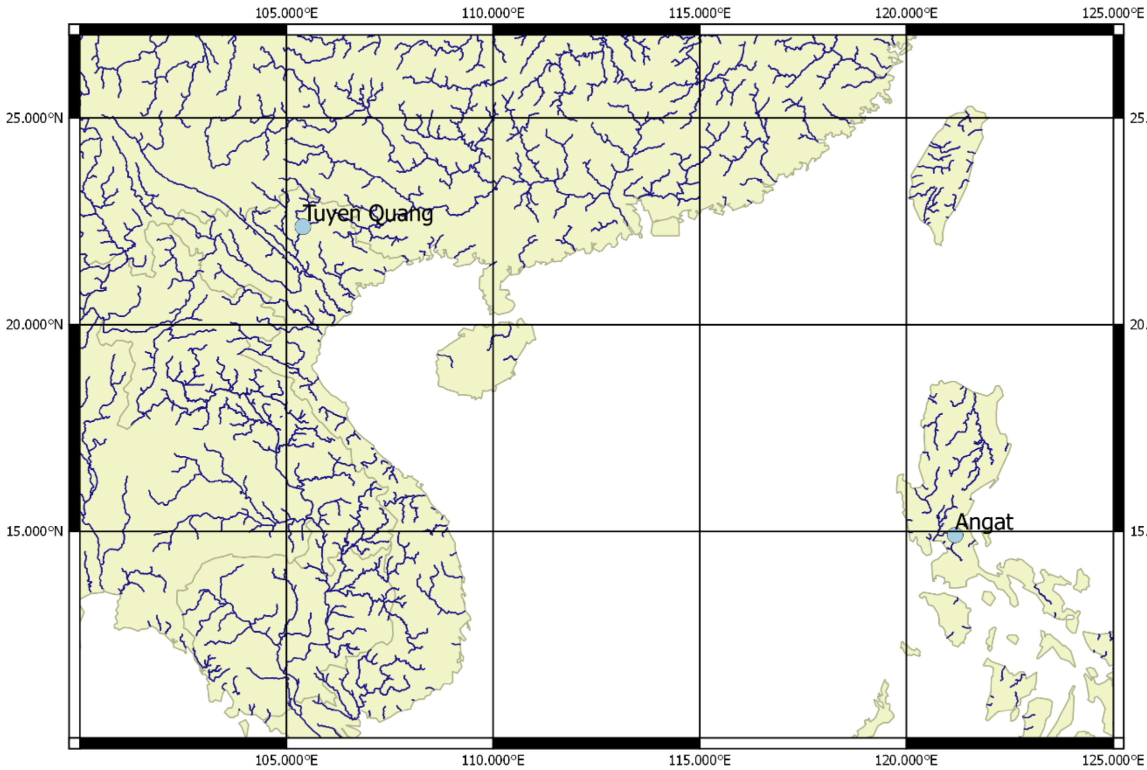

Figure 6: geographic locations of reservoirs in Southeast Asia together with major rivers

4 New proposed reservoir simulation method

A new reservoir simulation method is proposed that makes a difference between within-year reservoir behaviour and over-year reservoir behaviour. It is not hard to imagine that within-year behaviour takes place in every reservoir due to seasonality, while over-year behaviour is restricted to reservoirs of a certain relative size. Large reservoirs thus have more capacity to account for demand fluctuations. This reservoir scheme calculates within-year reservoir outflow and over-year reservoir outflow as two separate processes that can be turned on or off in accordance with the requirements of the model user: if a reservoir is classified as a within-year reservoir only within-year processes could be applied, if a reservoir is classified as an over-year reservoir both within-year and over-year processes could be applied. The new proposed reservoir simulation method will run on a daily time step, although for the Central Asian reservoirs where data is available on a 10 day interval, the reservoir simulation method will run on a 10 day time step. Compared to other existing reservoir simulation models, the effect of the impoundment ratio is taken into account for every reservoir, rather than for relatively small reservoirs only and it is the first time that data on long-term climatic conditions are used for reservoir storage simulations. There is no distinction between reservoirs with different purposes in the new reservoir scheme.

4.1 Within-year simulation

The within-year reservoir scheme takes into account the average meteorology or hydrology to define an operational year. Compared to other studies (e.g. Hanasaki et al. (2006); Haddeland et al. (2006) who define the start of an operational year as the first month that river flow does not exceed the average river flow, this study defines the start of an operational year as the first month that river flow starts to exceed the average river flow. Instead of taking the month that the reservoir is at its fullest, which is often at the end of the flood season, the month that the reservoir is theoretically at its emptiest is chosen as the starting date for the reservoir operational year. This is at the end of the dry season. After this the wet period stops before the river flow drops below the average river flow. The rest of the operational year is defined as the dry period. On this way, within-year reservoir simulations can be simulated in an explicit way: water that enters the reservoir in the wet season can be stored in the wet season and released later in the dry season of the same year. It must be said that not every area in the world shows clearly identifiable wet and dry seasons, or sometimes there are even more than one wet season. This method will only be applied on reservoirs that show one clear wet a dry season. To define a wet and dry season within an operational year, long term hydrological models (using long term data) should be invoked to define natural reservoir inflow. In case that reservoir inflow is already heavily affected by upstream human influences (e.g. other reservoirs or irrigation supply), these should be modelled first prior to modelling the current reservoir. If historical inflow time series are present, these could be used in order to define the start of the operational year as well the lengths of the wet and dry period.

At this point, there are two seasons in the year which are defined as the wet and the dry season. Hanasaki et al. (2006) gives an empirical relation between the impoundment ratio of a reservoir and the reservoir inflow. It states that for reservoirs with impoundment ratios < 0.5y, the reservoir outflow is dependent on reservoir inflow. The smaller the impoundment ratio, the more dependent the reservoir outflow is on reservoir inflow. The bigger the impoundment ratio, the less dependent the reservoir outflow is on reservoir inflow. This study also takes into account the impoundment ratio in order to define the reservoir outflow as a part of the inflow, however average inflow is not taken into account. For the defined wet period, the reservoir outflow is defined as the actual inflow times a factor between 0 and 1 to account for reservoir storage increase during wet period. In the dry period, the actual inflow is increased by adding the reservoir storage accumulated during the wet season divided by the duration of the dry period.

As for the reservoir module designed by Hanasaki et al. (2006), it is assumed that relatively small reservoirs (with small impoundment ratios) have relatively little storage and need to spill water before the reservoir gets full. Larger reservoirs (with larger impoundment ratios) are more flexible in reservoir storage management. On this way they can better store high discharges than small reservoirs. The reservoir inflow and the active storage of the reservoir are two relatively easy to obtain parameters of a reservoir. These can be used to calculate the impoundment ratio. The hypothesis that will be tested is that small reservoirs spill relatively more water in dry periods than large reservoir do. In order to test this hypothesis, data on the 16 available reservoirs is processed in order to determine the relation between the impoundment ratio of the reservoir and the reservoir outflow in periods that are defined as wet.

Figure 7 shows the observed relations between the relative reservoir outflows in the wet season (Q_{out}/Q_{in} wet season) and the impoundment ratios for 16 reservoirs. Although there is no one-to-one trend observable, it is clear that relatively small reservoirs tend to show higher Q_{out}/Q_{in} ratios in the wet season. An empirical relation is drawn that gives an approximate relation between the impoundment ratio IR and the Q_{out}/Q_{in} in wet seasons defined as outflow ratio r(-):

$$r = \frac{Q_{out}}{Q_{in}} = 0.55 * e^{(-1.8*IR)} + 0.45 \qquad \text{(eq. 20)}$$

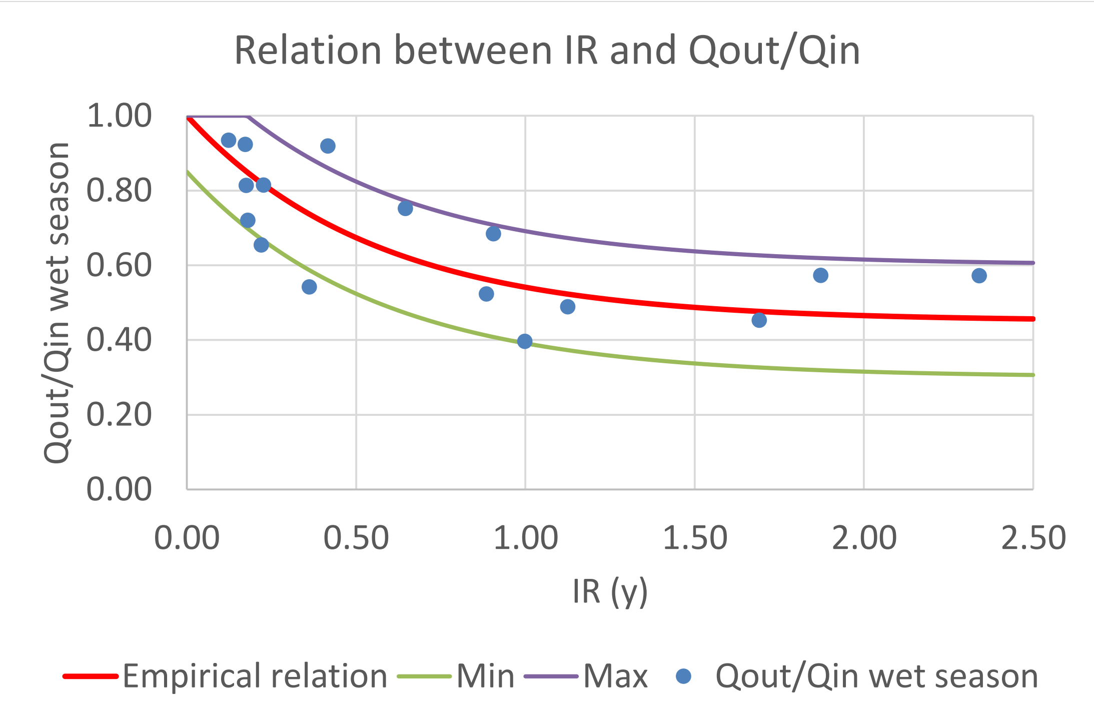

Figure 7: relation between reservoir impoundment ratio (IR) and Q_{out}/Q_{in} in wet season

The within-year scheme will be represented as:

$$Q_{out,wy'i,j,k} = \begin{cases} r * Q_{in_{i,j,k}} & mon_{fld,beg} \leq j \leq mon_{fld,end} \\ Q_{in_{i,j,k}} + \dfrac{\left(\sum_{j=mon_{fld,beg,k}}^{mon_{fld,end,k}} \left(\sum_{i=1}^{last} (1-r) * Q_{in_{i,j,k}}\right)\right)}{\sum_{j=mon_{fld,end,k}+1}^{mon_{fld,beg,k+1}-1} \left(\sum_{i=1}^{last} n_{i,j,k}\right)} & j > mon_{fld,end} \end{cases} \quad \text{(eq. 21)}$$

where $Q_{out,wy_{i,j,k}}$ = within-year reservoir outflow on day *i* in month *j* in operational year *k* (m^3/s), $Q_{in_{i,j,k}}$ = the reservoir inflow on day *i* in month *j* in operational year *k* (m^3/s), *r* = outflow ratio (-), $mon_{fld,beg,k}$ = the first month of the flood season in operational year *k*, $mon_{fld,end,k}$ = the last month of the flood season in operational year *k*, $n_{i,j,k}$ = a day *i* in month *j* and operational year *k*.

Since there is no one-to-one relation between the impoundment ratio *IR* and the outflow ratio r, a sensitivity analysis will show the sensitivity for fluctuations of *r*. If a value of 0.15 is added or subtracted from the set empirical relation for *r*, a certain bandwidth is obtained containing 13/16 reservoirs, which is the majority of this sample. This sensitivity analysis, together with the sensitivity analysis of other models is further described in section 5.2. The results of the sensitivity analysis and the results obtained with other reservoir schemes are presented in section 6.1.

4.2 Over-year simulation

The over-year reservoir outflow scheme makes use of the SPEI to correct the outflow in order to represent over-year reservoir storage. Lorenzo-Lacruz et al. (2010) already indicated the usefulness of the flexible time scales of SPEI in order to represent reservoir storage. There are several methods to obtain SPEI time series for the time periods of interest. The most convenient choice to obtain SPEI time series is by using a C++ program developed by the Spanish Scientific Research Council (CSIC) (http://digital.csic.es/handle/10261/10002). In order to use this program, time series of monthly precipitation and monthly average temperature for a certain area and period of interest should be filled in to obtain SPEI time series over this area and period of interest. Multiple databases are available online where monthly precipitation and temperature datasets could be retrieved. After this, these distributed datasets need to be resampled and averaged to one number for the area of interest, the area upstream of a reservoir. This area upstream of a reservoir could be obtained by DEM delineation. After this, SPEI time series could be calculated for the area of interest by using the C++ program.

For this study, it was considered that this method is too time-consuming. Therefore, a different approach was decided upon. At the moment of writing, SPEI time series for January 1950 – May 2015 for a significant part of the land masses of the world are available online in the SPEI Global Drought Monitor (http://sac.csic.es/spei/map/maps.html). Here, SPEI values could be retrieved on a global scale, on a regional scale and over single grid cells. Single grid cells in the SPEI Global Drought Monitor have a 0.5 degrees spatial resolution and monthly time resolution. SPEI time-scales between 1 and 48 months are provided. The calibration period of the SPEI is set from January 1950 – December 2010, which means that this period is used for calculation of average drought values. SPEI time series on a regional scale need to be retrieved to get average values over an upstream reservoir catchment. Only rectangular regions could be selected, what indicates that not the exact outlines of catchments upstream of reservoirs could be retrieved. For this study, it is assumed that enveloping rectangular outlines give a representative value for the average SPEI in upstream reservoir catchments.

An important assumption is that the reservoir storage is normally distributed, thus storage of reservoirs has a long-term mean and standard deviation. Observed reservoir storages are converted to standardized storages by subtracting the mean long-term observed storage and division by the long term standard deviation. On this way, reservoir storages become in the same order of magnitude as the SPEI values.

The next step is to find the optimal SPEI time scale that gives the best SPEI matches with the reservoir storage fluctuations. However, no previous study exactly indicates how this should be determined. Lorenzo-Lacruz et al. (2010) say that the inertia of the inflow and the hyper annual character of the managed system contribute a lot to the optimal SPEI time scale. An earlier study by Vicente-Serrano et al. (2005) said that it is necessary to consider the impoundment ratio, the type of supplied demand and the management pattern which can have a significant effect on the optimal time scale. Therefore, an analysis on the 16 reservoirs with data is done to find out if there is a relation between the impoundment ratio and the optimal SPEI time scale.

Figure 8 shows the observed relations between the optimal SPEI time scales and the impoundment ratios for 16 reservoirs. As can be observed, there is no single relation between the impoundment ratio and the optimal SPEI time scale. This means that next to the impoundment ratio, there are more factors that have an effect on the optimal SPEI time scale for a reservoir. However it could be observed that for many reservoirs with low impoundment ratios (*IR* < 1), the optimal SPEI time scale is in the order of magnitude of 12 months. For reservoirs that have relatively large impoundment ratios is this optimum generally higher, however still large differences appear. For Lake Powell in the USA, it seemed that that correlation between the optimal SPEI time scale and the impoundment ratio was still growing after 48 months (*IR*=1.88 years), which is the maximum SPEI time scale that could be retrieved from the SPEI Global Drought Monitor. Compared to Flaming Gorge reservoir for example that has a larger impoundment ratio, the difference is substantial (*IR*=2.34 years, Optimal SPEI time scale=18 months).

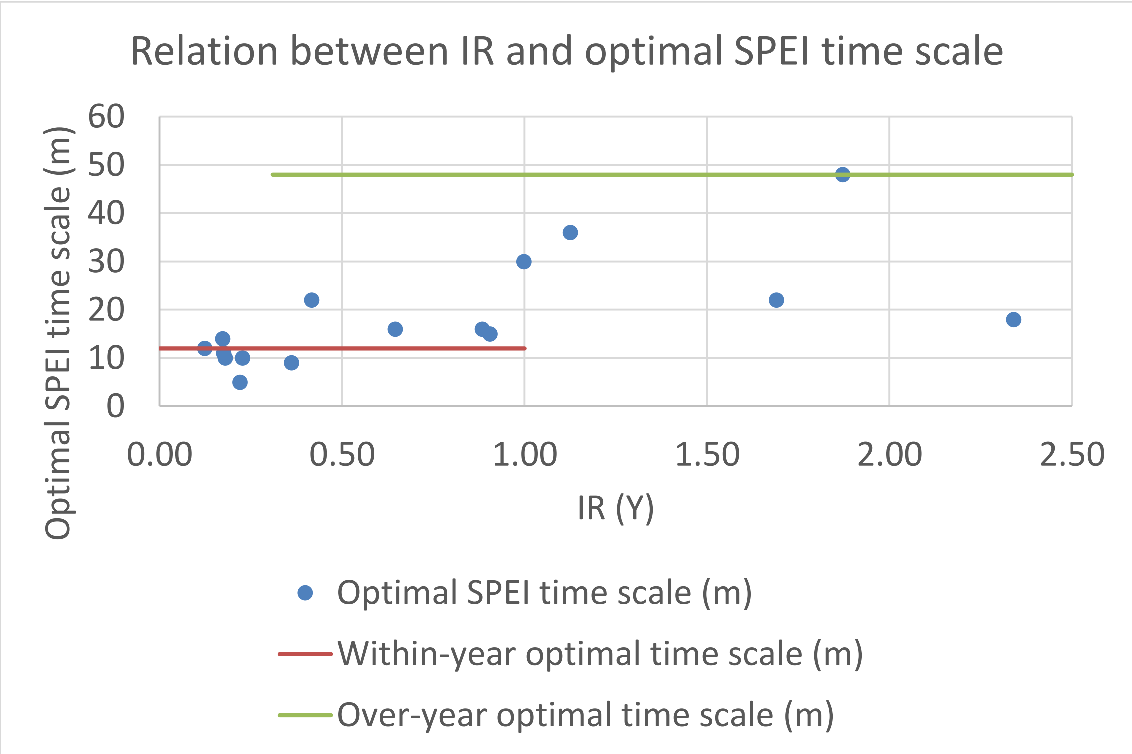

Figure 8: relation between reservoir impoundment ratio (IR) and optimal SPEI time scale

In order to use the SPEI in the over-year reservoir outflow scheme, assumptions have to be done to get further. Therefore a 'least unacceptable' SPEI time scale should be decided upon. To find this out, correlations between standardized storage and SPEI on different time scales for clearly over-year reservoirs are plotted. Figure 9, Figure 10, Figure 11 and Figure 12 show this correlation for Lake Powell, Seminoe reservoir, Flaming Gorge reservoir and Toktogul reservoir respectively. Although the best correlation is always for different SPEI time scales, the correlation does not deteriorate significantly compared to the optimal correlated SPEI time scale for Seminoe reservoir, Flaming Gorge reservoir and Toktogul reservoir if a SPEI time scale of 48 months is decided upon. This SPEI time scale is considered as the optimal SPEI time scale in this study, see Figure 8. In the sensitivity analysis, see section 5.2, it will be checked what the influence is of always assuming a SPEI time scale of 48 months rather than the specific optimized time scale per reservoir.

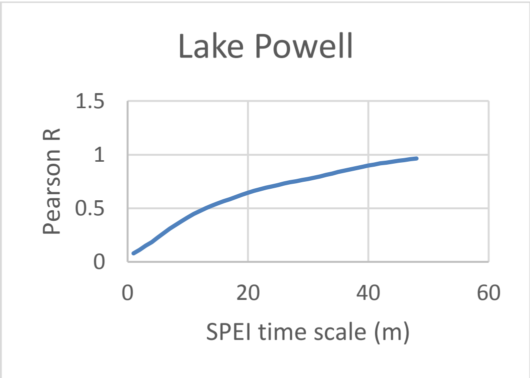

Figure 9: correlation SPEI per time scale with standardized storage Lake Powell

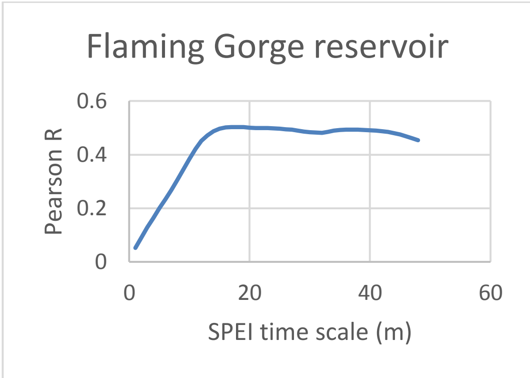

Figure 11: correlation SPEI per time scale with standardized storage Flaming Gorge reservoir

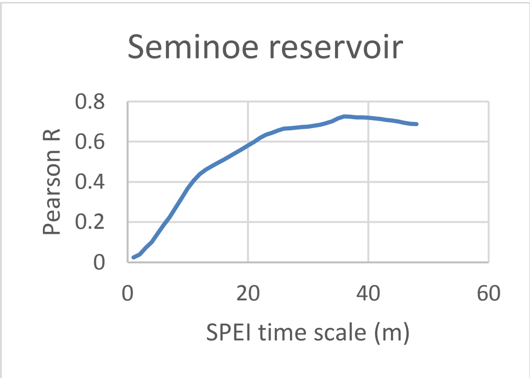

Figure 10: correlation SPEI per time scale with standardized storage Seminoe reservoir

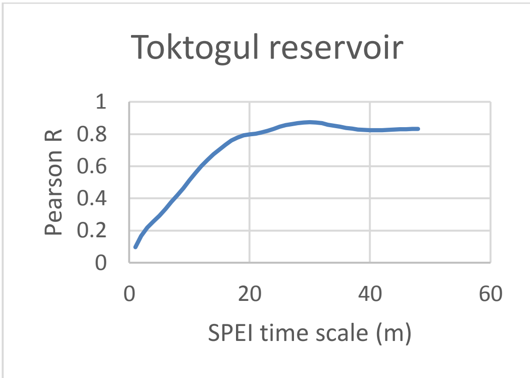

Figure 12: correlation SPEI per time scale with standardized storage Toktogul reservoir

Now it is decided to use a SPEI time scale of 48 months in order to simulate over-year storage behaviour of over-year reservoirs, a calculation algorithm that converts the SPEI values to additional outflow should be established. In fact, outflow calculated by the within-year reservoir scheme should be increased or decreased so that over-year storage fluctuations are observable in modelled storage time series. The first step to achieve this is to determine the mean reservoir storage and the standard deviations of monthly reservoir storage values for a reservoir. A convenient way to do is to use historical observations of reservoir storage values. This study uses in-situ data of 16 reservoirs and assumes that reservoir storages are normally distributed. Since in-situ data on reservoir storage is not actively shared for most reservoirs on the world, methods that include remote sensing observations can contribute to the acquirement of long term reservoir storage data.

After the determination of mean and standard deviation of storage, SPEI values are multiplied by this standard deviation and added to the mean reservoir storage in order to get monthly approximate storage time series. It must be noted that these storage time series do not involve actual data on storage but only the storage that is calculated by using the SPEI time scale of 48 months.

Next, monthly outflow time series are obtained by dividing the storage difference of two consecutive months by time in that last month. For every calendar year, these monthly super positioned outflow are added so that a yearly super positioned outflow time series is obtained. This means now that yearly outflow time series for calendar year *l* are obtained that are based on the difference between the $SPEI_{48}$ storage in December in year *l-1* and December in year *l-2*. The reason that not the monthly outflow time series are used in final outflow time series is that otherwise outflow time series with many monthly peaks and drops are obtained, while the essence of the over-year reservoir outflow scheme is to simulate over-year storage effects rather than monthly discharge fluctuations. By choosing an interval of one year rather than one month it means that monthly discharge fluctuations that bring noise in the outflow time series are extinguished.

The over-year scheme, provided that a reservoir is an over-year reservoir, will be represented as:

$$Q_{out,oy,i,j,l} = \frac{((SPEI_{48} * \sigma_S) + \mu_S)_{december,l-1} - ((SPEI_{48} * \sigma_S) + \mu_S)_{december,l-2}}{\sum_{j=1}^{12}(\sum_{i=1}^{last} n_{i,j,l}) * 86400} \qquad \text{(eq. 22)}$$

where $Q_{out,oy,I,j,l}$ = the reservoir outflow on day *i* in month *j* in calendar year *l* (m^3/s), *SPEI48* = the Standardized Precipitation Evapotranspiration Index on a time scale of 48 months, σ_S = the standard deviation of the reservoir storage (m^3), μ_S = the average reservoir storage (m^3), $n_{i,j,l}$ = a day *i* in month *j* and calendar year *l*.

The SPEI based outflow time series are added to the within-year reservoir scheme outflow results for the year after the SPEI yearly outflow values are calculated, provided that a reservoir is an over-year reservoir. Total reservoir outflow Q_{out} (m^3/s) is defined as:

$$Q_{out} = \begin{cases} Q_{out,wy} & if\ reservoir = within - year\ reservoir \\ Q_{out,wy} + Q_{out,oy} & if\ reservoir = over - year\ reservoir \end{cases} \qquad \text{(eq. 23)}$$

Results of this reservoir simulation scheme, that consists of a within-year and an optional over-year scheme are tested on sensitivity in section 6.1 and compared with other reservoir simulation schemes in section 6.2.

5 Methods

This chapter describes the methods performed in this study to compare different non data-driven reservoir simulation schemes. First it is determined which reservoir schemes will be subjected to a sensitivity analysis. Next, a sensitivity analysis is described and the reservoirs that serve as case study during the sensitivity analysis. This sensitivity analysis will denote the sensitivities of diverse parameters in the preselected reservoir schemes. Afterwards a method is proposed how the preselected reservoir schemes are compared with each other.

5.1 Reservoir scheme selection

In chapter 2, an overview is given of currently available reservoir simulation methods. Furthermore, a new reservoir scheme is developed in chapter 4. All reservoir schemes have their advantages and disadvantages, however there has been no study yet that denominates them. In order to use the reservoir scheme, the demanded data needs to be available for example. Furthermore, a reservoir model should not be calibrated on local circumstances, since a model should be applicable worldwide if data is scarce. Too many calibration parameters lead to unacceptable results. Finally, a reservoir scheme should not be too simplistic. Based on these requirements, three reservoir schemes are selected plus the newly developed scheme that will be assessed on parameter sensitivity and performance compared to each other. These other three schemes are:

- Scheme developed by Neitsch et al. (2002) and implemented in the current version of SWAT (abbreviated as SWAT)
- Scheme developed by Hanasaki et al. (2006) (abbreviated as HIRS and HNIRS for irrigation included respectively not included)
- Natural lake outflow scheme developed by Döll et al. (2003) (abbreviated as NLOS)

The reservoir scheme developed in chapter 4 will be abbreviated as DVRS which stands for De Vos Reservoir Scheme.

5.2 Sensitivity analysis

Three out of four selected reservoir schemes (except NLOS) have their sensitivities that should be well interpreted by the model user. The sensitivities are located in the parameters that should be filled in but for which data is generally not directly available. Other sensitivities are located in the parameters that could not be filled in but are considered to be calibrated on available time series data by the model user. The sensitivity analysis assessment will be based on the normalized root-mean-square error (NRMSE), which is defined as the root-mean-square error (RMSE) divided by the mean of all observed values. The variables that will be assessed are the modelled reservoir outflow Q_{out} and the modelled reservoir storage S. The parameters that will be tested on their sensitivity per model and which are assumed to be known by the model user are described below. Table 5 shows in table form the parameters per model that are tested on sensitivity.

Table 5: overview of parameters tested on sensitivitiy per model

Model	Parameters tested on sensitivity
SWAT	ND_{targ}
HNIRS/HIRS	$(IR/0.5)^2$
DVRS	r and SPEI time scale

5.2.1 SWAT

SWAT assumes two target storages within a year that stay the same for the entire modelling period. Over-year storage fluctuations are not accounted for on this way. This suggest that SWAT is only applicable to within-year reservoirs. During this study, the two target storages described by SWAT are represented by the maximum reservoir storage and the dead reservoir storage. Furthermore, two months have to be included that represent the begin and end of the flood season: $mon_{fld,beg}$ and $mon_{fld,end}$. These months are chosen as 3 months in advance of the flood season and the dry season respectively. One parameter that needs to be calibrated is the so called ND_{targ}, which determines a certain number of days in which the target storage needs to be approached. The parameters that are chosen are the optimized ND_{targ} value that gives the optimal outflow simulation results in terms of NRMSE and an ND_{targ} value that is represented as:

$$ND_{targ} = IR * 365 * 0.25 \qquad \text{(eq. 24)}$$

where *IR* is the impoundment ratio (y). The factor 0.25 is added because it is assumed that a within-year reservoir is filling for maximum a quarter of the year. The impoundment ratio adds the relative size of the reservoir. A relatively small reservoir is theoretically filled earlier than a relatively large reservoir. Soil moisture dependency is not taken into account during this study due to simplification reasons and unavailability of data.

5.2.2 HIRS and HNIRS

HIRS and HNIRS together actually describe one reservoir scheme. The only difference is that HIRS is designed to be applied for reservoirs that have irrigation as a main task, while HNIRS should be applied for reservoirs that do not have irrigation as a main task. Both schemes correct for the *IR* of a reservoir in case a reservoir is small enough (*IR* < 0.5y). The reservoir outflow becomes more inflow dependent if *IR* becomes smaller. The exact relation that is described however raises questions. In Figure 13, the inflow dependency relation for small reservoirs (*IR* < 0.5y) is presented. If reservoir data of sixteen available reservoirs are used to calculate the optimal inflow dependency for a particular reservoir, it seems that most of the reservoirs are not as inflow dependent as indicated by Hanasaki et al. (2006). The outflows of 6 out of 8 reservoirs are significantly less inflow dependent than indicated by the drawn relation. To indicate the sensitivities of this relation, a new empirical relation is proposed that gives a better relation between the inflow dependency and *IR* for the available eight reservoirs. The new relation for modelling small reservoirs that is applied in the sensitivity analysis is represented as:

$$Q_{out} = \begin{cases} k_{rls} * Q'_{out}, (IR \geq 0.5y) \\ (\frac{IR}{0.5})^{\beta} k_{rls} * Q'_{out} + \{1 - (\frac{IR}{0.5})^{\beta}\} Q_{in,avg}, (0y \leq IR < 0.5y) \end{cases} \qquad \text{(eq. 25)}$$

where *β* is a new constant (0.8).

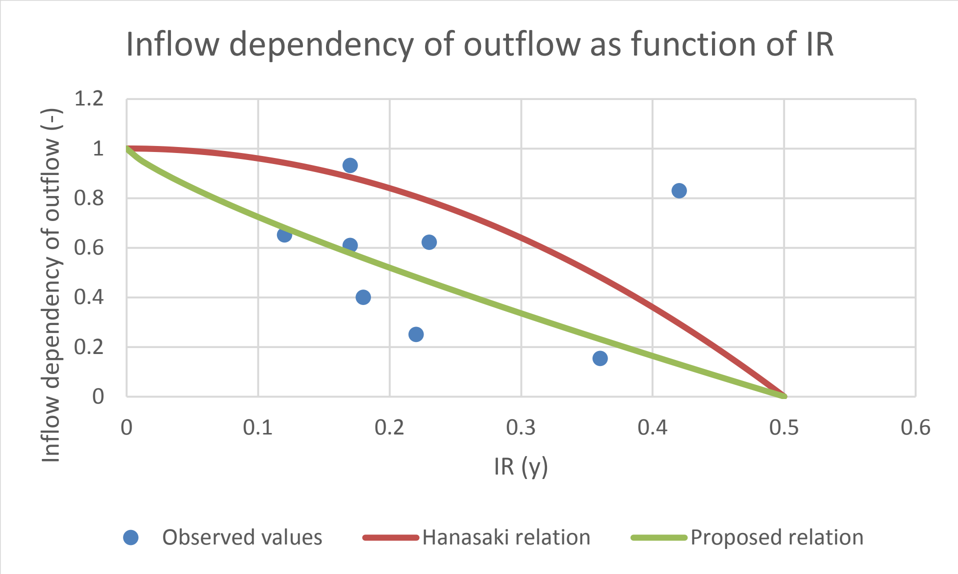

Figure 13: inflow dependency of outflow as function of IR

It should be clear that the sensitivity analysis for this scheme could only be done for reservoirs for which it holds that $IR < 0.5y$. Since there is no data available on irrigation, the sensitivity analysis of HIRS will not be treated here. However, some very basic assumptions are done in order to get irrigation values. These assumptions will be further explained and applied in section 5.3.

5.2.3 DVRS

As already indicated in chapter 4, the within-year module shows no one-to-one relation between the impoundment ratio and the outflow ratio in wet seasons r. There seems to be a certain bandwidth around a proposed relation where most of the outflow ratios fall into. Therefore, a sensitivity analysis will be performed to show how the model performance decreases if the empirically established outflow ratio-impoundment ratio relation is followed compared with the observed outflow ratio per reservoir.

The over-year module also needs input data that is not always available to the model user. Data that are necessary are SPEI time series, a value for the mean reservoir storage, a value for the standard deviation of reservoir storage and a value for an optimal SPEI time scale. SPEI time series could be easily retrieved online, see chapter 4. In theory, the mean value and standard deviation for reservoir storage could be obtained from remotely sensed data. The only parameter that does not have a clear value is the SPEI time scale. In chapter 4, it is said that the correlation between the optimized SPEI time scale and does not seem to decrease significantly if a time scale of 48 months is chosen for most reservoirs. Therefore, a sensitivity analysis will be performed to show how much the model performance in combination with the within-year reservoir module decreases if the SPEI time scale of 48 months is used compared to the optimized SPEI time scale.

5.2.4 Case studies

This sensitivity analysis will be performed for three reservoirs that should be representative examples of one within-year reservoir on the one hand and two over-year reservoirs on the other hand. Nurek reservoir in Tajikistan is chosen as a case study for within-year reservoirs. Here data is available on a 10 day interval. Seminoe reservoir in the USA is chosen as a case study for over-year reservoirs. Data is here available on a daily interval. Also Toktogul reservoir in Kyrgyzstan is chosen as a case study for over-year reservoirs. Here data is available on a 10 day interval. The sensitivity analysis is performed for the time resolution that is available for all three respective reservoirs. However, for visualization reasons the graphs will show monthly averaged results.

5.3 Methods comparison

After the sensitivity analysis, reservoir simulation schemes are compared with each other for all available (16) reservoirs. The method comparison assessment will be based on the normalized root-mean-square error (NRMSE) and the coefficient of determination (r^2). The first coefficient gives information about the errors made where a value of 0 means a perfect fit, the latter coefficient gives information about the correlation of the data where a value of 1 means a perfect fit. The variables that will be assessed are the modelled reservoir outflow $Q_{out,mod}$ and the modelled reservoir storage S_{mod}. Furthermore, reservoir simulation schemes are also compared with the no-modelling scenario (inflow equals outflow) and the scenario where outflow equals average inflow. Simulation results are also assessed by visual inspection on five criteria:

- Height of high outflow peaks
- Timing of high outflow peaks
- Low flow periods
- Within-year storage fluctuation range
- Over-year storage fluctuations

For every reservoir routing scheme the original formulas as in literature are taken, so except for DVRS it means that the reservoir routing schemes are not optimized for the available dataset. In case calibration parameters need to be determined, the non-optimized values as already assumed in the sensitivity analysis are chosen as a parameter value.

Additional to HNIRS, now also HIRS will be applied if applicable. This scheme needs water demand data in order to give reservoir outflow results. It needs data on irrigation water demand, domestic water demand and industrial water demand respectively. For this study, it was not possible to come up with any of the three data demands, so only an (over)simplified form of irrigation water demand d_{irg} will be defined. Irrigation water demand d_{irg} will be simplified by using the crop coefficient (k_c) value of a common crop in the concerning study area. For the western USA, it was found that a common crop is alfalfa grass (Putnam et al. 2000). Since a cropping calendar was not found, it is assumed that irrigation for alfalfa grass takes place from the beginning of February until the end of July. Table 6 shows the exact k_c values for the four respective growing stage periods of alfalfa grass (Allen et al. 1998). Figure 14 shows the yearly repetitive cropping pattern in time if k_c values for alfalfa grass are considered.

Table 6: applied k_c values for respective alfalfa cropping periods

Time period	Crop period name	k_c value
February	Initial period	0.4
March - May	Crop development period	0.4 – 1.2
June	Midseason period	1.2
July	Late period	1.15

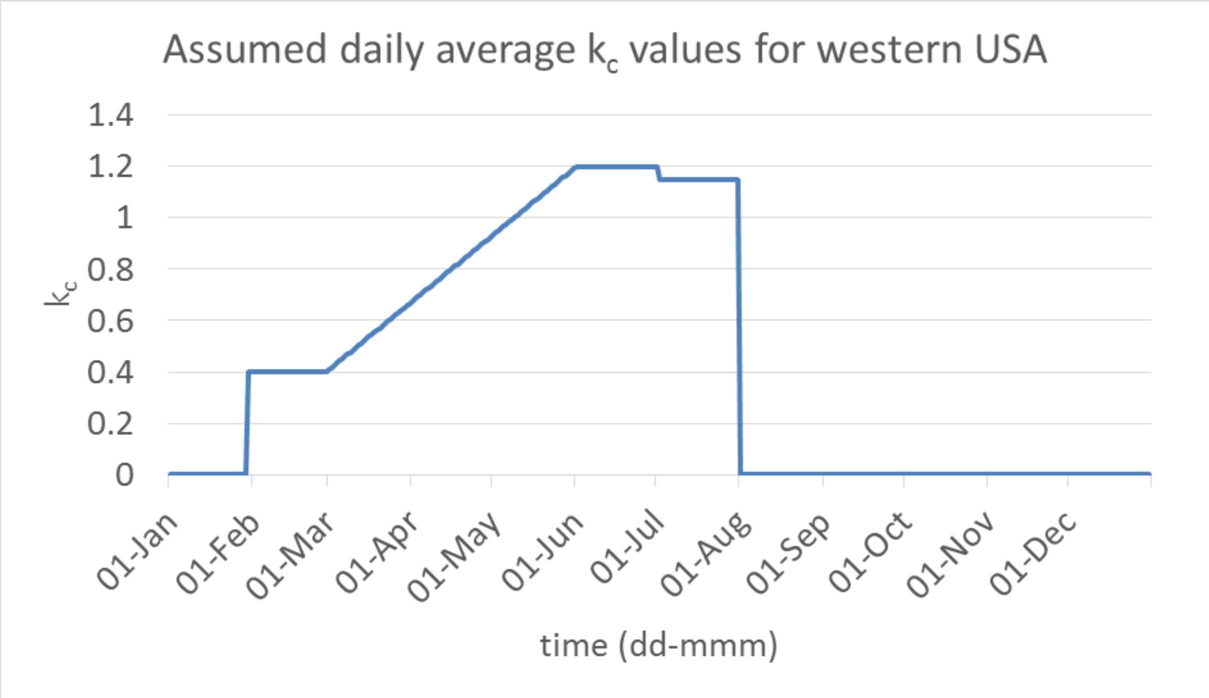

Figure 14: yearly repetitive daily k_c values for alfalfa grass in western USA

HIRS needs daily water demand values which are relative to the annual water demand. This means $0 \leq d_{irg} \leq 1$.To determine these relative daily water demand values, first all daily k_c values for one entire year are added. After that, the daily relative water demands are determined by dividing the daily k_c values by the sum of the daily k_c values. Note that the inclusion of HIRS in the model comparison analysis will only be performed for the American reservoirs and not for the rest of the reservoirs. The reasons of this are lack of data or the fact that the reservoirs are not used for irrigation purposes.

6 Results

This chapter shows the results of the sensitivity analysis and the method comparison. The sensitivity analysis is done for three reservoirs: one within-year reservoir and two over-year reservoirs. The method comparison is done for all 16 available reservoirs.

6.1 Sensitivity analysis

The sensitivity analysis is performed for three selected reservoirs. Although calculations are performed over longer time series, the sensitivity analysis results are shown in graphs for only eight years (2002 – 2009). The reason for this is that interpretation becomes difficult if longer time series are shown. For the same reason the monthly averaged time series are shown rather than the calculated daily time series.

6.1.1 SWAT

The sensitivity analysis for SWAT is done for all three selected reservoirs. Table 7 gives the data used in the sensitivity analysis for SWAT for Nurek reservoir. Figure 15 shows the observed reservoir in- and outflow (Q_{in} and $Q_{out,obs}$), simulated reservoir outflow according to this study's proposed relation ($Q_{out,mod,rel}$) and simulated reservoir outflow that follows from the optimum fit by adapting ND_{targ} ($Q_{out,mod,opt}$) for Nurek reservoir. It seems that optimizing ND_{targ} does not mean that the entire outflow time series is improved. Random peaks are often correctly decreased, however outflows in the beginning of the low flow periods remain too low. Figure 16 shows the observed reservoir storage (S_{obs}), simulated reservoir storage according to this study's proposed relation ($S_{mod,rel}$) and simulated reservoir storage that follows from the optimum fit for $Q_{out,mod,opt}$ by adapting ND_{targ} ($S_{mod,opt}$) for Nurek reservoir. Here it seems that the optimized outflow does not lead to a better representation of the storage. The outflow with ND_{targ} based on this study's proposed relation shows a better representation of the storage change amplitude.

Table 7: data sensitivity analysis SWAT for ND_{targ} for Nurek reservoir

	ND_{targ}	S_{max} (m^3)	S_{min} (m^3)	$mon_{fld,beg}$	$mon_{fld,end}$	NRMSE Q_{out} Nurek	NRMSE S Nurek
SWAT optimized	53.00	1.05E+10	6.00E+09	January	July	0.53	0.24
SWAT relation	16.43	1.05E+10	6.00E+09	January	July	0.96	0.16

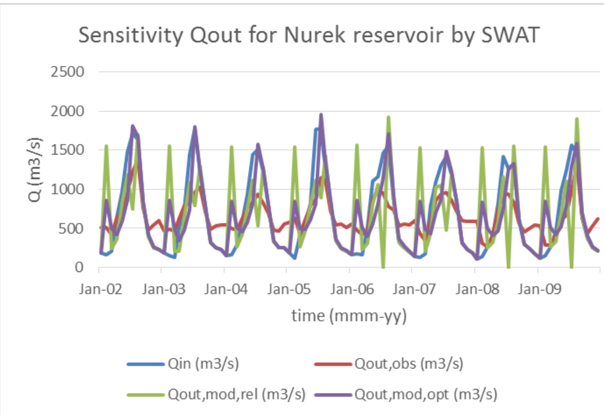

Figure 15: sensitivity Q_{out} for Nurek reservoir by SWAT

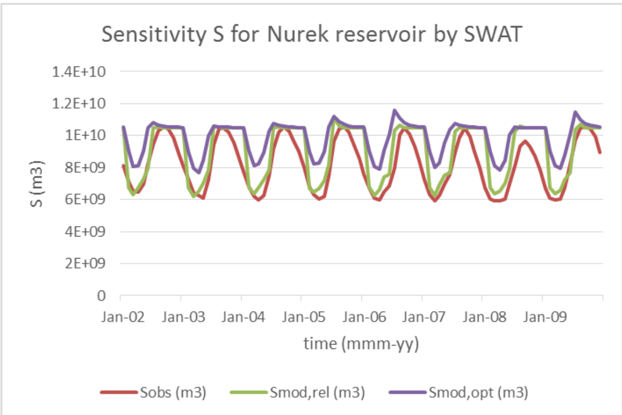

Figure 16: sensitivity S for Nurek reservoir by SWAT

Table 8 gives the data used in the sensitivity analysis for SWAT for Toktogul reservoir. Figure 17 shows Q_{in}, $Q_{out,obs}$, $Q_{out,mod,rel}$ and $Q_{out,mod,opt}$ for Toktogul reservoir. Optimizing ND_{targ} has a significant effect on improving outflow time series. This study's proposed relation for determining ND_{targ} leads to a too sharp reservoir outflow time series; outflow is always unrealistically over- or underestimated. The optimized ND_{targ} value leads to a more smoothened time series for reservoir outflow, however random peaks or drops are still occurring. Figure 18 shows S_{obs}, $S_{mod,rel}$ and $S_{mod,opt}$ for Toktogul reservoir. Although the model is optimized for simulating Q_{out}, it seems that S is not well reproduced. $S_{mod,opt}$ shows a too low storage amplitude and over-year storage fluctuations are not accounted for. $S_{mod,rel}$ shows a better representation of the storage amplitude, but also over-year storage fluctuations are hardly accounted for.

Table 8: data sensitivity analysis SWAT for ND_{targ} for Toktogul reservoir

	ND_{targ}	S_{max} (m^3)	S_{min} (m^3)	$mon_{fld,beg}$	$mon_{fld,end}$	NRMSE Q_{out} Toktogul	NRMSE S Toktogul
SWAT optimized	252.00	1.95E+10	5.50E+09	January	June	0.75	0.46
SWAT relation	91.25	1.95E+10	5.50E+09	January	June	1.16	0.32

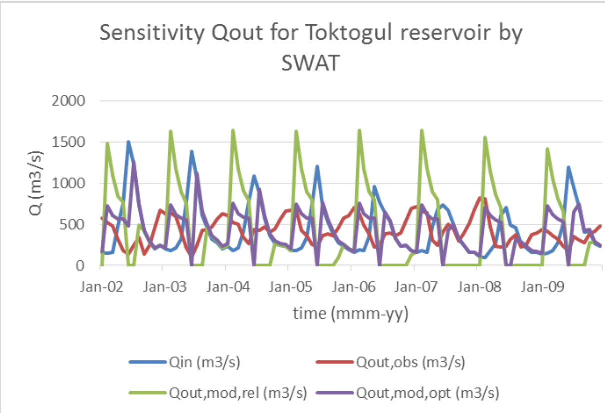

Figure 17: sensitivity Q_{out} for Toktogul reservoir by SWAT

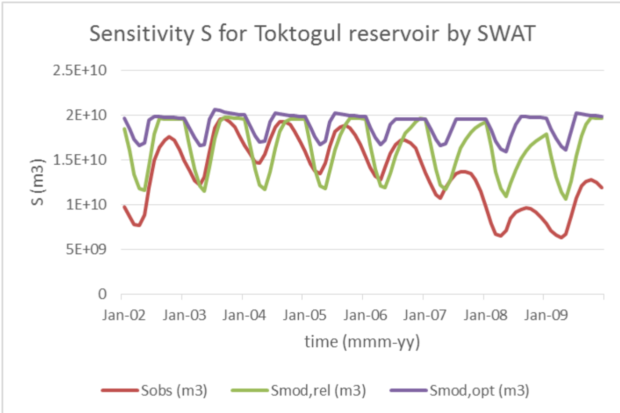

Figure 18: sensitivity S for Toktogul reservoir by SWAT

Table 9 gives the data used in the sensitivity analysis for SWAT for Seminoe reservoir. Figure 19 shows Q_{in}, $Q_{out,obs}$, $Q_{out,mod,rel}$ and $Q_{out,mod,opt}$ for Seminoe reservoir. Optimizing ND_{targ} has a significant effect on improving outflow time series. By optimizing ND_{targ}, more smoothened outflow time series are obtained rather than peaky time series, however the timing of the peaks does not become better. Figure 20 shows S_{obs}, $S_{mod,rel}$ and $S_{mod,opt}$ for Toktogul reservoir. It seems that the optimized reservoir outflow time series does not optimize the storage time series as well. Using this study's proposed relation for determination of ND_{targ} shows a better representation of reservoir storage regarding over-year behaviour, although the storage amplitudes are significantly increased compared to the observed storage amplitudes.

Table 9: data sensitivity analysis SWAT for ND_{targ} Seminoe reservoir

	ND_{targ}	S_{max} (m^3)	S_{min} (m^3)	$mon_{fld,beg}$	$mon_{fld,end}$	NRMSE Q_{out} Seminoe	NRMSE S Seminoe
SWAT optimized	244.00	1.25E+09	6.86E+05	December	May	1.09	0.63
SWAT relation	91.25	1.25E+09	6.86E+05	December	May	1.29	0.37

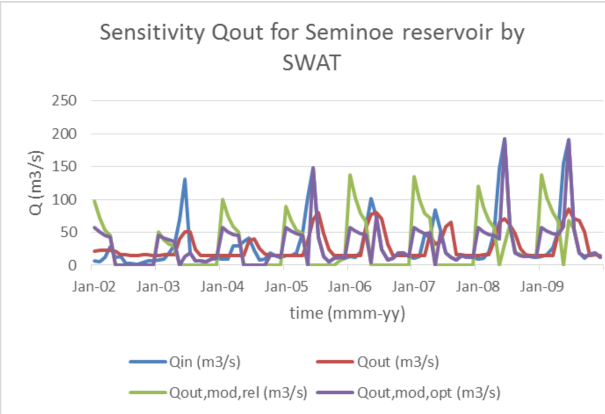

Figure 19: sensitivity Q_{out} for Seminoe reservoir by SWAT

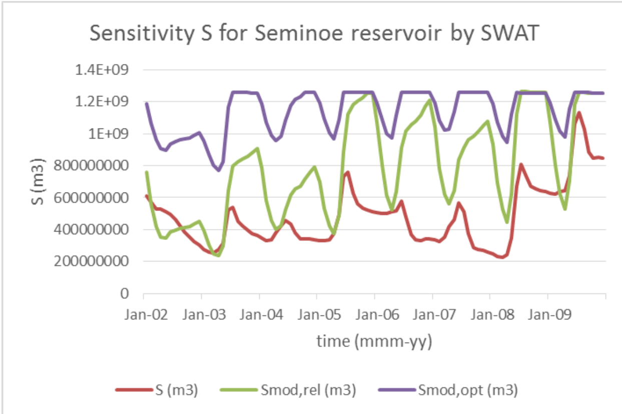

Figure 20: sensitivity S for Seminoe reservoir by SWAT

The examples shown above indicate that using SWAT with optimized parameters for simulating reservoir outflow does not mean that reservoir storage is also well simulated using these optimized parameters. The representation of storage even gets significantly worse with optimized parameters. Obviously, ND_{targ} is not a parameter that can be calibrated in order to deliver optimum results for both reservoir outflow and storage.

6.1.2 HNIRS

The sensitivity analysis for HNIRS is only done for Nurek reservoir, since this is the only reservoir that is 'small enough' (IR < 0.5y) to account for the effect of actual inflow on reservoir outflow. Table 10 gives the data used in the sensitivity analysis for HNIRS for Nurek reservoir. Figure 21 shows the observed reservoir in- and outflow (Q_{in} and $Q_{out,obs}$), simulated reservoir outflow according to the original inflow dependency relation ($Q_{out,mod,ori}$) and simulated reservoir outflow that follows from this study's proposed inflow dependency relation based on eight available within-year reservoirs ($Q_{out,mod,rel}$) for Nurek reservoir. It seems that the original relation tends to overestimate the reservoir outflow in high-flow periods and underestimate the reservoir outflow in low flow periods. This study's new proposed inflow relationship improves for this case the order of magnitude of outflow in both high-flow periods and low-flow periods as well. Figure 22 shows the observed reservoir storage (S_{obs}), simulated reservoir storage according to the original inflow dependency relation ($S_{mod,ori}$) and simulated reservoir storage that follows from this study's proposed inflow dependency relation based on eight available within-year reservoirs ($S_{mod,rel}$) for Nurek reservoir. It can be observed that the original relation does not seem to simulate a good reservoir storage amplitude. This study's new proposed inflow relationship improves the storage simulation compared to the original inflow dependency relation.

Table 10: data sensitivity analysis HNIRS for parameter β for Nurek reservoir

	α	β	IR (y)	S_{max} (m^3)	S_{min} (m^3)	NRMSE Q_{out} Nurek	NRMSE S Nurek
HNIRS original	0.85	2.00	0.18	1.05E+10	6.00E+09	0.45	0.19
HNIRS relation	0.85	0.80	0.18	1.05E+10	6.00E+09	0.28	0.10

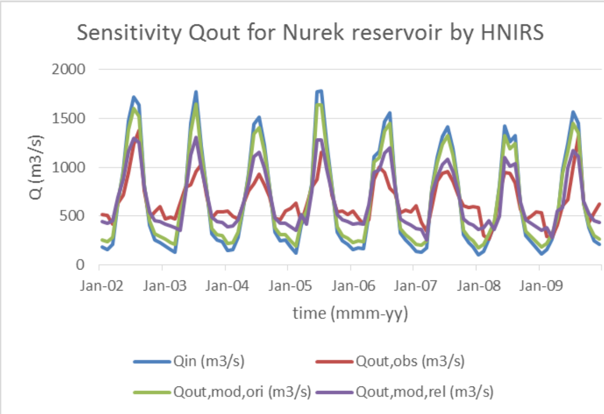

Figure 21: sensitivity Q_{out} for Nurek reservoir by HNIRS

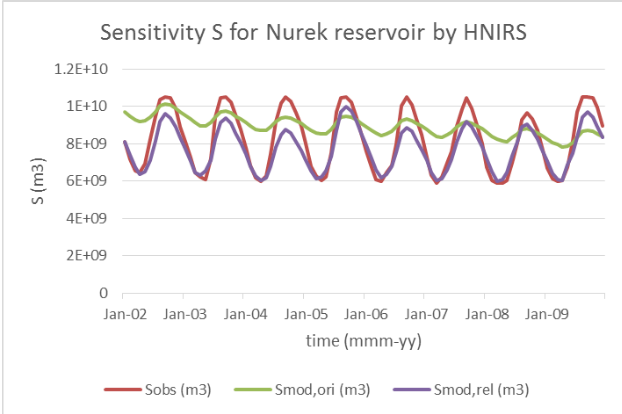

Figure 22: sensitivity S for Nurek reservoir by HNIRS

From this sensitivity analysis it can be inferred that inflow dependency is quite important in order to simulate reservoir outflow and storage for the right order of magnitude. It is already indicated that the original proposed inflow dependency relation by Hanasaki et al. (2006) overestimates inflow dependency for the reservoirs that are studied in this research. It is expected that the original inflow dependency relation is proposed based on too few data or conceptually wrong assumptions are done. Perhaps there are more parameters that have an influence on the inflow dependency of reservoirs rather than only impoundment ratio of the reservoir such as the coefficient of variation C_v of inflow.

6.1.3 DVRS

The sensitivity analysis for DVRS is done for two parameters: the outflow ratio *r* for both within-year and over-year reservoirs and the SPEI time scale for over-year reservoirs. The sensitivity of the outflow ratio *r* is tested for all three reservoirs. The sensitivity of the SPEI time scale is tested for Toktogul reservoir and Seminoe reservoir only.

Outflow ratio r

Table 11 gives the data used in the sensitivity analysis for DVRS within-year for Nurek reservoir. Figure 23 shows the observed reservoir in- and outflow (Q_{in} and $Q_{out,obs}$), simulated reservoir outflow according to the proposed outflow ratio *r* relation ($Q_{out,mod,pro}$) and simulated reservoir outflow that follows from using the outflow ratio *r* for which optimal outflow results are obtained ($Q_{out,mod,opt}$) for Nurek reservoir. $Q_{out,mod,pro}$ tends to overestimate for this case reservoir outflow in high flow periods and it tends to underestimate reservoir outflow in low flow periods. By applying the outflow relation *r* for which the best outflow simulation is obtained, it seems indeed that the overestimated peaks in high flow periods decrease and that in low flow periods the flows are increases in order to get more realistic outflow values. Figure 24 shows the observed reservoir storage (S_{obs}), simulated reservoir storage according to the proposed outflow ratio *r* relation ($S_{mod,pro}$) and simulated reservoir storage that follows from using the outflow ratio *r* for which optimal outflow results are obtained ($S_{mod,opt}$) for Nurek reservoir.

Table 11: data sensitivity analysis DVRS within-year for outflow ratio r for Nurek reservoir

		IR (y)	outflow ratio r	NRMSE Q_{out} Nurek	NRMSE S Nurek
DVRS wy optimized		0.18	0.72	0.28	0.07
DVRS wy proposed		0.18	0.85	0.36	0.18

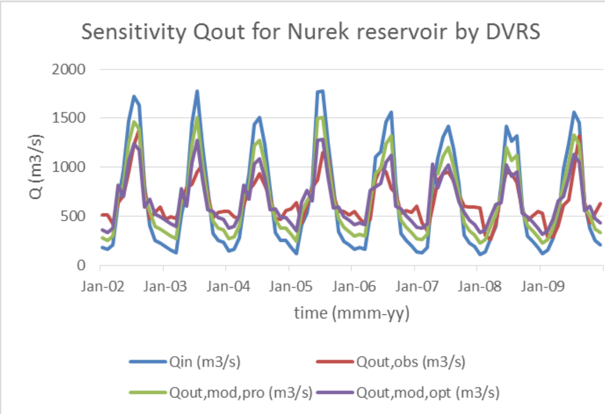

Figure 23: sensitivity Q_{out} for Nurek reservoir by DVRS (within-year)

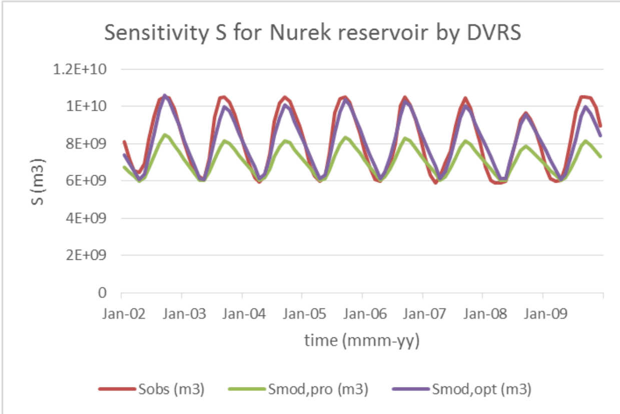

Figure 24: sensitivity S for Nurek reservoir by DVRS (within-year)

Table 12 gives the data used in the sensitivity analysis for DVRS within-year for Toktogul reservoir. Figure 25 shows Q_{in}, Q_{out}, $Q_{out,mod,pro}$ and $Q_{out,mod,opt}$ for Toktogul reservoir. It seems that there are no big differences if the proposed relation to determine the outflow relation *r* is used or if the outflow ratio *r* is used for which reservoir outflow simulation is optimized. Figure 26 shows S_{obs}, $S_{mod,pro}$ and $S_{mod,opt}$ for Toktogul reservoir. Here it can be observed that reservoir storage fluctuations are not significantly changed by optimizing the outflow ratio *r*.

Table 12: data sensitivity analysis DVRS within-year for outflow ratio r for Toktogul reservoir

	IR (y)	outflow ratio r	μ_S (m^3)	σ_S (m^3)	SPEI time scale (m)	NRMSE Q_{out} Toktogul	NRMSE S Toktogul
DVRS wy optimized	1.00	0.40	1.35E+10	3.80E+09	30	0.51	0.22
DVRS wy proposed	1.00	0.54	1.35E+10	3.80E+09	48	0.57	0.26

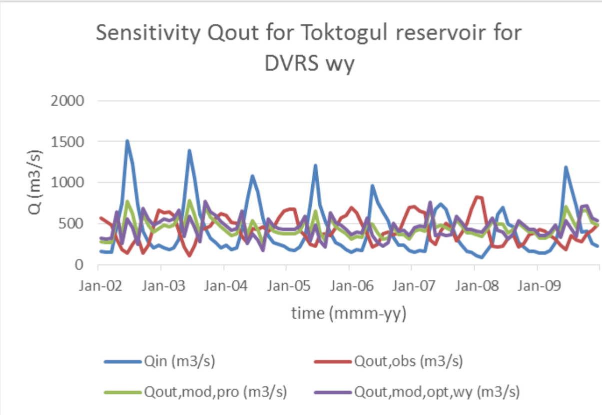

Figure 25: sensitivity Q_{out} for Toktogul reservoir by DVRS (within-year)

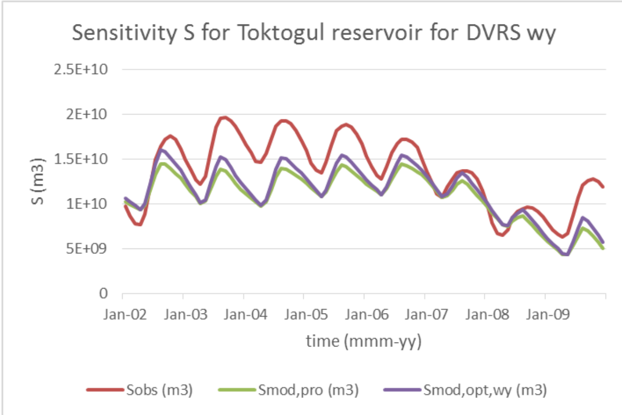

Figure 26: sensitivity S for Toktogul reservoir by DVRS (within-year)

Table 13 gives the data used in the sensitivity analysis for DVRS within-year for Seminoe reservoir. Figure 27 shows Q_{in}, Q_{out}, $Q_{out,mod,pro}$ and $Q_{out,mod,opt}$ for Seminoe reservoir. For this particular reservoir, it seems that there is hardly any difference between the optimized outflow ratio *r* and the outflow ratio *r* that follows from the proposed relation. This can be observed in the outflow time series, since $Q_{out,mod,pro}$ and $Q_{out,mod,opt}$ nearly overlap for the entire presented period. Figure 28 shows S_{obs}, $S_{mod,pro}$ and $S_{mod,opt}$ for Seminoe reservoir. Also here it seems that a rather small change in outflow ratio *r* hardly shows any effects regarding the storage simulation.

Table 13: data sensitivity analysis DVRS within-year for outflow ratio r for Seminoe reservoir

	IR (y)	outflow ratio r	μ_S (m^3)	σ_S (m^3)	SPEI time scale (m)	NRMSE Q_{out} Seminoe	NRMSE S Seminoe
DVRS wy optimized	1.13	0.49	7.31E+08	2.77E+08	48	1.22	0.28
DVRS wy proposed	1.13	0.52	7.31E+08	2.77E+08	48	1.24	0.28

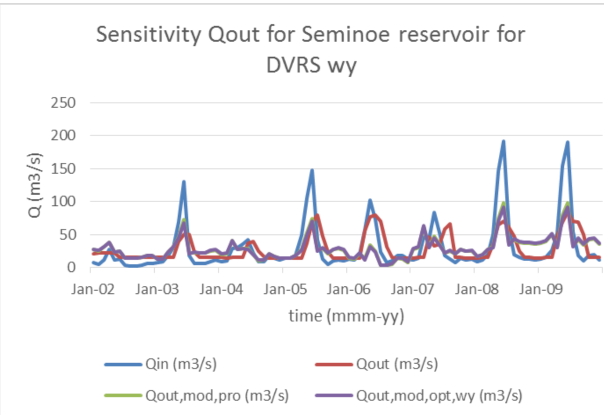

Figure 27: sensitivity Q_{out} for Seminoe reservoir by DVRS (within-year)

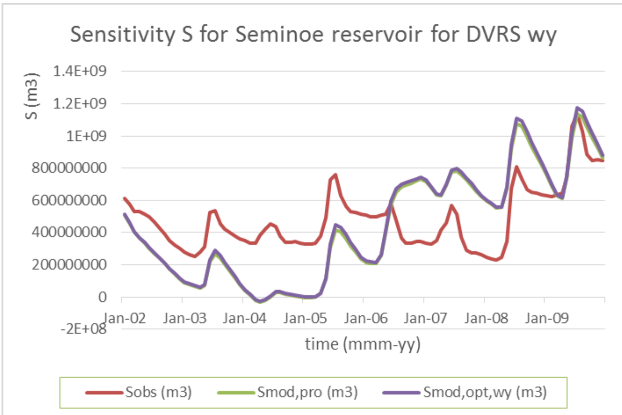

Figure 28: sensitivity S for Seminoe reservoir by DVRS (within-year)

The above shown examples indicate that the proposed outflow ratio relation *r* gives a relatively close match regarding reservoir outflow and storage simulation compared with the optimum outflow ratio

r. The model performance for the reservoirs with large impoundment ratios seems not to decrease significantly if another outflow ratio r is used. For the within-year reservoir the performance decreases more significantly, but still it seems that the loss in model performance by using the proposed outflow ratio r relation is quite acceptable.

SPEI time scale

Table 14 gives the data used in the sensitivity analysis for DVRS over-year for Toktogul reservoir. Figure 29 shows the observed reservoir in- and outflow (Q_{in} and $Q_{out,obs}$), simulated reservoir outflow according to the proposed outflow ratio r relation ($Q_{out,mod,pro}$) and simulated reservoir outflow that follows from using the outflow ratio r for which optimal outflow results are obtained ($Q_{out,mod,opt}$) for Toktogul reservoir. It seems that choosing a different SPEI time scale only has a minor effect on reservoir outflow time series. Figure 30 shows the observed reservoir storage (S_{obs}), simulated reservoir storage according to the proposed outflow ratio r relation ($S_{mod,pro}$) and simulated reservoir storage that follows from using the outflow ratio r for which optimal outflow results are obtained ($S_{mod,opt}$) for Toktogul reservoir. Compared to the effect on reservoir outflow time series, here it seems that choosing a different SPEI value has significant effects on simulated reservoir storage. Especially in the middle part of the presented time series the difference in storage simulation is clear. However, both SPEI time scales are correct in the way that they both simulate a storage decrease at the end of the time series.

Table 14: data sensitivity analysis DVRS over-year for SPEI time scale for Toktogul reservoir

	IR (y)	outflow ratio r	μ_S (m³)	σ_S (m³)	SPEI time scale (m)	NRMSE Q_{out} Toktogul	NRMSE S Toktogul
DVRS oy optimized	1.00	0.54	1.35E+10	3.80E+09	30	0.59	0.36
DVRS oy proposed	1.00	0.54	1.35E+10	3.80E+09	48	0.57	0.26

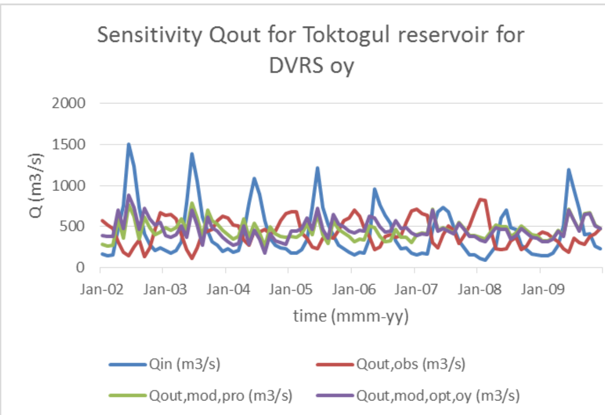

Figure 29: sensitivity Q_{out} for Toktogul reservoir by DVRS (over-year)

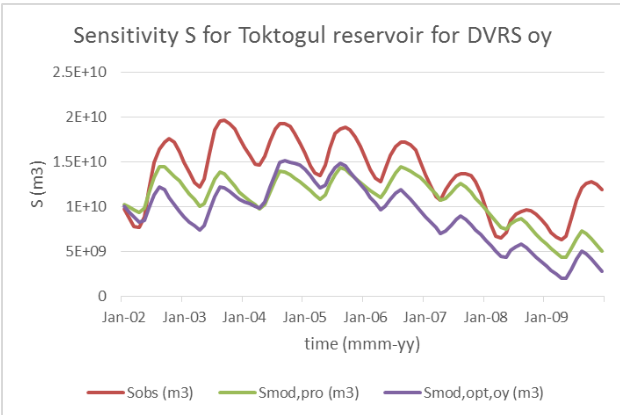

Figure 30: sensitivity S for Toktogul reservoir by DVRS (over-year)

Table 15 gives the data used in the sensitivity analysis for DVRS over-year for Seminoe reservoir. Figure 31 shows Q_{in}, Q_{out}, $Q_{out,mod,pro}$ and $Q_{out,mod,opt}$ for Seminoe reservoir. Apparently, choosing a different SPEI time scale does not influence the reservoir outflow behaviour for this reservoir significantly. Only in the middle of the presented time series it seems that the SPEI time scale for which the reservoir simulation is optimized shows altered outflows. Figure 32 shows S_{obs}, $S_{mod,pro}$ and $S_{mod,opt}$ for Seminoe reservoir. Here it is clearly visible that for a time period of eight years, it makes a significant difference which SPEI time scale is decided upon to use in reservoir simulation. Especially in the middle part of the time series it seems that the model is sensitive for different SPEI time scales. Despite that, both SPEI time scales are correct in the way they simulate storage decrease in the beginning and storage increase in the end of the presented period.

Table 15: data sensitivity analysis DVRS over-year for SPEI time scale for Seminoe reservoir

	IR (y)	outflow ratio r	μ_S (m^3)	σ_S (m^3)	SPEI time scale (m)	NRMSE Q_{out} Seminoe	NRMSE S Seminoe
DVRS oy optimized	1.13	0.52	7.31E+08	2.77E+08	36	1.25	0.29
DVRS oy proposed	1.13	0.52	7.31E+08	2.77E+08	48	1.24	0.28

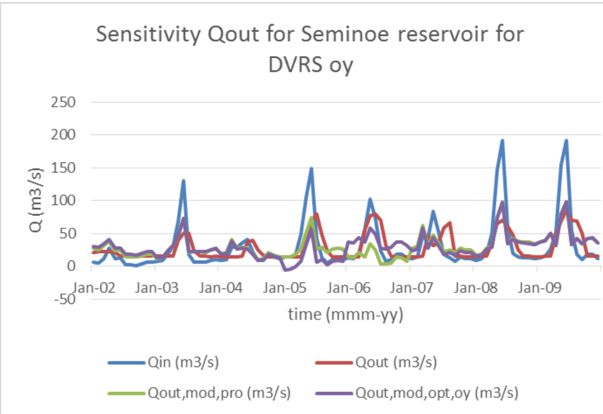

Figure 31: sensitivity Q_{out} for Seminoe reservoir by DVRS (over-year)

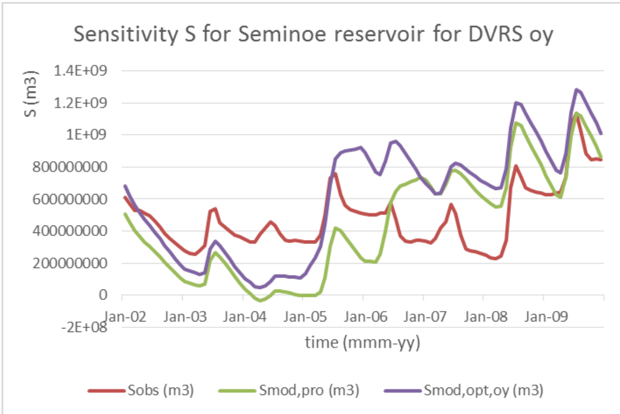

Figure 32: sensitivity S for Seminoe reservoir by DVRS (over-year)

For Seminoe reservoir, a relatively large time scale is available. To show the sensitivities of choosing a different SPEI time scale, a long-term storage time series is shown in Figure 33. It can be observed that for both SPEI time scales, over-year storage fluctuations are relatively well simulated. This means that it is indeed correct that for this reservoir it is not problematic to choose a near-optimum SPEI time scale rather than an optimum SPEI time scale in order to simulate over-year storage fluctuations.

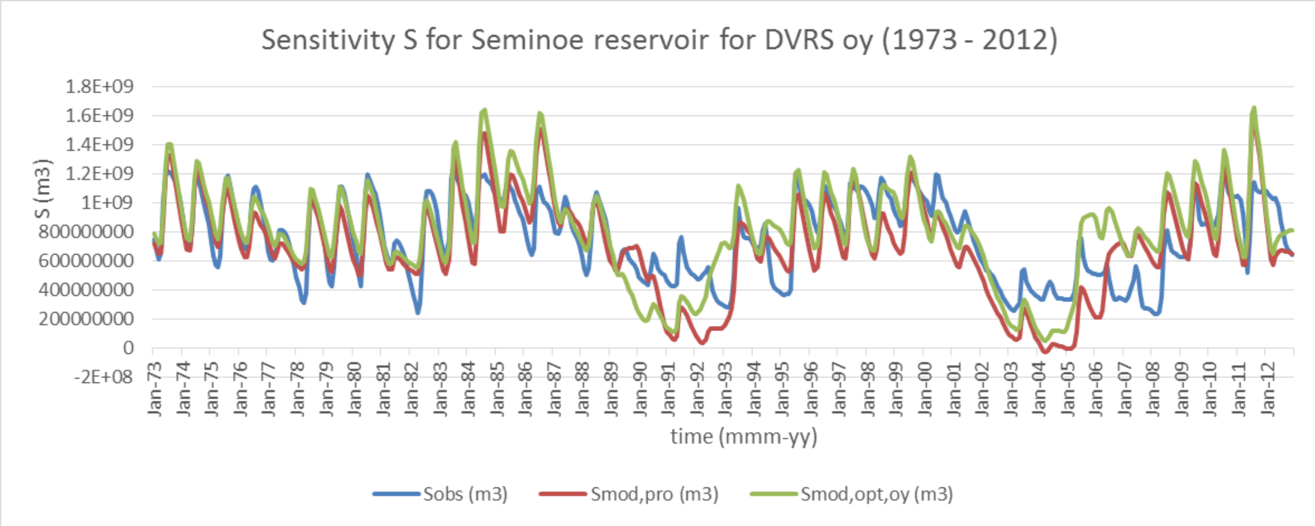

Figure 33: long-term sensitivity S for Seminoe reservoir by DVRS (over-year)

From this sensitivity analysis, it could be deduced that for over-year storage modelling, it is not problematic to choose a near-optimal SPEI time scale. Over-year storage fluctuations are well reproduced by taking into account the near-optimal and the optimal SPEI time scale. Reservoir outflow is hardly influenced by adopting a near-optimal SPEI time scale instead of an optimal SPEI time scale.

6.2 Method comparison

The method comparison is performed for all 16 reservoirs with available data. First a table is shown with the assessment dates and time resolution for every reservoir. Hereafter two tables with NRMSE values divided by the mean observed values and r^2 values for both $Q_{out,mod}$ and S_{mod} are given. Afterwards the model performance per reservoir model is assessed by visual inspection of monthly averaged graphs over time periods of three to eight years (depending on the data availability).

6.2.1 Assessment details

Table 16 shows the assessment dates and resolution for the sixteen available reservoirs. One reason that not the same dates are used as there is data available for is that some reservoir schemes needed the reservoir scheme to start and end in the middle of a calendar year. A second reason is that reservoirs are not always in a steady operational state, indicating that the reservoir was still filling up during times that data is available.

Table 16: assessment dates and -resolution for 16 available reservoirs

Reservoir name	Assessment dates	Assessment resolution
Canyon Ferry Lake	2002 – 2012	1 day
Lake Elwell	2002 – 2012	1 day
Bull Lake reservoir	2002 – 2012	1 day
Seminoe reservoir	1973 – 2012	1 day
Flaming Gorge reservoir	1973 – 2012	1 day
Blue Mesa reservoir	1972 – 2012	1 day
Lake Powell	1983 – 2012	1 day
Tyuyamuyun reservoir	2002 – 2009	10 days
Nurek reservoir	2002 – 2009	10 days
Kayrakkum reservoir	2002 – 2009	10 days
Andizhan reservoir	2002 – 2009	10 days
Charvak reservoir	2002 – 2009	10 days
Chardara reservoir	2002 – 2009	10 days
Toktogul reservoir	2002 – 2009	10 days
Tuyen Quang reservoir	2008 – 2010	1 day
Angat reservoir	2010 – 2012	1 day

6.2.2 Goodness of fit parameters

Table 17 shows the results of the assessments of the five tested reservoir simulation models in terms of NRMSE divided by mean observed values and r^2 for Q_{out}. For comparison reasons also the results are added if actual inflow or averaged inflow are used as a proxy for reservoir outflow. Overall performance is bad to moderate at best. It can be observed that for mostly all reservoirs, SWAT is the worst performing model.

In case of the American reservoirs, NLOS tends to show the best results. To explain this good fit, one has to observe the discharge graphs, see Appendix A. It seems that the highest outflow peak for many of the American reservoirs is observed right after the peak for the reservoir inflow (e.g. for Lake Elwell, Bull Lake and Blue Mesa reservoir). This shows that more reservoir outflow is generated in times that storages are high (which occurs after times of high inflows) rather than inflows are high. NLOS is a simulation scheme that does not take into account the actual inflow, but only considers actual storage in order to calculate reservoir outflow. For these cases that reservoir outflow is high if storage is high, NLOS seems to be an acceptable model. Two other models (HNIRS and DVRS) that take into account only actual inflow and/or average inflow to simulate outflow can never reproduce the outflow 'delay' reproduced by NLOS.

For the other reservoirs located in Central Asia (Appendix B) and Southeast Asia (Appendix C), NLOS often does not give the best results. The main difference between the reservoirs in Asia and in the USA is the impoundment ratio. Reservoirs in the USA in this study generally have higher impoundment ratios than the Asian reservoirs. Because relatively small reservoirs tend to be more supply driven, high outflows can be expected when inflows are high as well. This seems to be true for every reservoir except for Toktogul reservoir that tends to store proportionally more water in high inflow periods. This specific abnormality can be explained by the fact that the impoundment ratio of Toktogul reservoir is relatively high compared to the other Asian reservoirs. The fact that small reservoirs are more likely to be supply driven is also the reason that for the Asian reservoirs the actual inflow as a proxy for outflow is just the best simulation method.

Table 17: discharge simulation results for all reservoirs in terms of NRMSE and r^2, best results are highlighted green, worst results are highlighted red

		Canyon Ferry	Lake Elwell	Bull Lake	Seminoe	Flaming Gorge	Blue Mesa	Lake Powell
NLOS	NRMSE	0.50	0.70	1.11	0.87	0.58	0.73	0.42
	r^2	0.49	0.39	0.46	0.38	0.30	0.26	0.47
SWAT	NRMSE	1.08	1.86	1.90	1.29	1.75	1.26	1.63
	r^2	0.09	0.00	0.00	0.17	0.01	0.03	0.00
HNIRS	NRMSE	0.58	0.89	1.47	0.82	0.70	0.68	0.59
	r^2	0.30	0.02	0.03	0.37	0.23	0.22	0.33
HIRS	NRMSE	0.77	0.94	1.14	0.96	0.95	0.88	0.79
	r^2	0.27	0.07	0.41	0.43	0.18	0.21	0.29
DVRS	NRMSE	0.32	0.90	1.40	1.24	1.17	0.71	0.50
	r^2	0.68	0.22	0.13	0.32	0.26	0.16	0.26
Q_{in}	NRMSE	0.51	1.69	1.65	1.16	0.92	1.16	0.89
	r^2	0.65	0.11	0.18	0.42	0.29	0.11	0.24
$Q_{in,avg}$	NRMSE	0.55	0.86	1.49	0.89	0.64	0.67	0.47
	r^2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

		Tyuya-muyun	Nurek	Kay-rakkum	Andizhan	Charvak	Chardara	Toktogul
NLOS	NRMSE	0.76	0.85	0.69	0.78	0.76	0.87	0.62
	r^2	0.51	0.45	0.23	0.44	0.44	0.06	0.07
SWAT	NRMSE	0.90	0.96	0.96	1.32	0.89	0.81	1.16
	r^2	0.33	0.12	0.07	0.02	0.15	0.13	0.04
HNIRS	NRMSE	0.39	0.45	0.32	0.81	0.39	0.59	0.37
	r^2	0.78	0.70	0.52	0.31	0.65	0.10	0.05
HIRS	NRMSE	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	r^2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DVRS	NRMSE	0.38	0.36	0.33	0.72	0.38	0.49	0.57
	r^2	0.78	0.67	0.44	0.48	0.63	0.14	0.21
Q_{in}	NRMSE	0.38	0.55	0.34	0.69	0.47	0.66	1.01
	r^2	0.81	0.70	0.51	0.53	0.65	0.09	0.38
$Q_{in,avg}$	NRMSE	0.82	0.36	0.41	0.97	0.63	0.37	0.38
	r^2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.

		Tuyen Quang	Angat
NLOS	NRMSE	1.00	0.88
	r^2	0.51	0.23
SWAT	NRMSE	1.10	1.07
	r^2	0.31	0.06
HNIRS	NRMSE	0.87	0.92
	r^2	0.53	0.12
HIRS	NRMSE	n.a.	n.a.
	r^2	n.a.	n.a.
DVRS	NRMSE	0.85	1.08
	r^2	0.53	0.05
Q_{in}	NRMSE	0.93	1.33
	r^2	0.53	0.07
$Q_{in,avg}$	NRMSE	1.16	0.71
	r^2	n.a.	n.a.

Table 18 shows the results of the assessments of the five tested reservoir simulation models in terms of NRMSE divided by mean observed values and r^2 for *S*. There are some similarities between the simulation results of Q_{out} and *S*, but also a significant amount of differences.

For the American reservoirs, it seems that SWAT is often the worst choice in simulation of storage. The reason for this can be declared by the fact that SWAT assumes just two target storages within an operational year. This means that over-year storage simulations are not taken into account at all by SWAT. The results indeed prove that not taking into account over-year storage fluctuations is a big limitation of SWAT in the case of over-year reservoirs. It is hard to say what the best method is in order to simulate storage for these American reservoirs. It is difficult to observe similarities of storage patterns in observed discharge, see Appendix A. The performances of HNIRS, HIRS and DVRS often look like each other and often one of those three models shows the best results. This may indicate that over-year storage correction (which all three models do) could lead to better storage simulations. However if one takes a look at Canyon Ferry reservoir, HNIRS and HIRS perform significantly worse than DVRS. A benefit of DVRS is that it takes into account a 'storage fluctuation range' but HNIRS and HIRS do not. In this case the actual storage fluctuation range is significantly smaller than the probable storage fluctuation range (=active reservoir storage).

In case of the Asian reservoirs (see Appendix B and Appendix C), best results are often obtained for DVRS. In section 5.2.2 it seemed that HNIRS compensates too much for small within-year reservoirs, meaning that the part of the outflow that consists of actual inflow is overestimated. The result of this is that for these reservoirs, the storage amplitude is underestimated. Since DVRS is calibrated on this dataset, it often gives the most representative results for storage simulation. It depends on the impoundment ratio of the reservoirs if SWAT is giving good storage simulation results. For two over-year reservoirs (Toktogul and Andizhan) it seems that SWAT gives the worst results. This is explained by the fact that SWAT does not correct for over-year storage simulations. For Nurek, Kayrakkum and Chardara reservoir however, SWAT gives a good representation for storage simulation. These reservoirs appear to show annual recurring reservoir storages. NLOS often shows the worst results.

Table 18: storage simulation results for all reservoirs in terms of NRMSE and r^2, best results are highlighted green, worst results are highlighted red

		Canyon Ferry	Lake Elwell	Bull Lake	Seminoe	Flaming Gorge	Blue Mesa	Lake Powell
NLOS	NRMSE	0.15	0.20	0.28	0.28	0.45	0.19	0.45
	r^2	0.55	0.80	0.49	0.46	0.51	0.57	0.36
SWAT	NRMSE	0.24	0.40	0.72	0.37	0.50	0.39	0.43
	r^2	0.32	0.43	0.04	0.44	0.40	0.50	0.37
HNIRS	NRMSE	0.30	0.23	0.39	0.24	0.20	0.23	0.20
	r^2	0.45	0.55	0.27	0.64	0.34	0.61	0.60
HIRS	NRMSE	0.40	0.22	0.35	0.25	0.22	0.25	0.21
	r^2	0.24	0.52	0.56	0.60	0.49	0.46	0.56
DVRS	NRMSE	0.11	0.13	0.69	0.28	0.20	0.33	0.16
	r^2	0.56	0.46	0.05	0.63	0.30	0.38	0.86
		Tyuya-muyun	**Nurek**	**Kay-rakkum**	**Andizhan**	**Charvak**	**Chardara**	**Toktogul**
NLOS	NRMSE	0.85	0.28	0.63	0.51	0.59	0.74	0.23
	r^2	0.24	0.21	0.05	0.44	0.41	0.35	0.38
SWAT	NRMSE	0.73	0.16	0.33	0.79	0.43	0.35	0.32
	r^2	0.07	0.72	0.68	0.00	0.51	0.39	0.29
HNIRS	NRMSE	0.44	0.19	0.42	0.49	0.35	0.54	0.14
	r^2	0.11	0.39	0.08	0.09	0.39	0.17	0.89
HIRS	NRMSE	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	r^2	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
DVRS	NRMSE	0.38	0.18	0.34	0.68	0.26	0.50	0.26
	r^2	0.24	0.90	0.58	0.13	0.60	0.54	0.69
		Tuyen Quang	**Angat**					
NLOS	NRMSE	1.12	0.88					
	r^2	0.16	0.89					
SWAT	NRMSE	0.95	0.82					
	r^2	0.26	0.23					
HNIRS	NRMSE	0.88	0.47					
	r^2	0.46	0.69					
HIRS	NRMSE	n.a.	n.a.					
	r^2	n.a.	n.a.					
DVRS	NRMSE	0.55	0.52					
	r^2	0.57	0.42					

6.2.3 Visual inspection of monthly averaged graphs

Since goodness of fit parameters do not show very good results in terms of absolute values (e.g. the 'best' r^2 value for discharge simulations for five simulation models often gives a value that does not exceed 0.30) and therefore not very informative, visual inspections are necessary to assess the results as well. The five reservoir models will be assessed on the representation of the following criteria:

- Height of high outflow peaks
- Timing of high outflow peaks
- Low flow periods
- Within-year storage fluctuation range
- Over-year storage fluctuations

Since there are 8/10 graphs per reservoir (4/5 simulations for both outflow simulations and storage simulations), the amount of graphs adds up to 142. For an overview of the graphs a reference is made to the Appendices: Appendix A for American reservoirs, Appendix B for reservoirs in Central Asia and Appendix C for reservoirs in Southeast Asia, which are attached at the end of this report. All three appendices contain graphs with modelled outflows compared with observed outflows and modelled storages compared with observed storages for three to eight years. Furthermore, Appendix A contains graphs with long-term modelled storage versus long-term observed storage for four reservoirs for which long-term time series were available. The results of the visual inspection could be found in Table 19. Visually acceptable results are classified as yes and visually unacceptable results are classified as no.

NLOS

NLOS shows better results for the American reservoirs than for the reservoirs in Central Asia, which is also found after inspection of NRMSE and r^2. For most American reservoirs, peak discharges are estimated in the right order of magnitude and the timing is right as well. For the Asian reservoirs this is also the case for some of the smaller reservoirs in terms of impoundment ratio, but not for all. Further it can be observed that for larger reservoirs in the USA the outflow recession limbs are significantly longer than observed. The reason for this is that reservoirs generally want to maintain a high water level once filled up at the end of the wet season, but NLOS tends to spill more once the water level is high.

Storage amplitudes are often underestimated for the Asian reservoirs. The storage simulation amplitude for American is often in the right order of magnitude. Further it could be observed that over-year storage fluctuations are not well represented for any over-year reservoir. This could be well observed at Toktogul reservoir and Lake Powell. These two issues indicate that NLOS has disadvantages if it is applied for very small reservoirs in terms of within-year storage simulation or if it is applied for large reservoirs in terms of over-year storage simulation. Storage simulation works well for relatively large reservoirs with relatively little over-year storage fluctuations such as Lake Elwell and Canyon Ferry reservoir.

SWAT

SWAT never shows good results for most of the tested reservoirs. Regarding discharge simulation, a combination of the right height and the right timing of the high discharge peak is never obtained. Therefore, SWAT cannot be seen as an appropriate model to simulate reservoir outflow if only very basic data is available.

There are some exceptions that the storage simulation results are good regarding both within-year simulation range and over-year simulation. These are mainly the reservoirs that do not show over-year storage behaviour, such as some reservoirs in Central Asia that have yearly recurring storage patterns that span the entire active storage as defined for the model (e.g. Nurek, Kayrakkum, Charvak and Chardara reservoir).

HNIRS

HNIRS does not show the right order of magnitude and right timing of peaks for reservoirs having larger impoundment ratios then 0.5y. For this reason HNIRS is not often a good model in these cases, but one has to say that this is also not always the case for other models. For example, Toktogul entirely turns around the hydrological regime in reality. All other models miscalculate the timing of the high outflow peaks, while HNIRS does not simulate peaks at all. For this particular case, HNIRS is thus the 'best' model, although the outflow simulation is not really good. For smaller reservoirs with impoundment ratios smaller than 0.5y, high outflows are overestimated and low flows are underestimated as earlier mentioned in section 5.2.2.

Within-year storage simulations are often not well represented by SWAT. Especially for the smaller reservoirs, within-year storage amplitudes are often significantly underestimated. This can be explained by the fact that high outflows are often overestimated and low flows are often underestimated for small reservoirs. For the larger reservoirs the storage amplitude is often in the right order of magnitude. Regarding over-year storage simulations it really depends if the active storage is fully used in the simulation period. If the HNIRS storage graph of Canyon Ferry reservoir is observed, it seems that the over-year storage simulation is much overestimated. The reason for this is that Canyon Ferry has a large active storage, while this storage capacity is not used in reality. Most of the other over-year reservoirs are well represented by HNIRS in terms of storage.

HIRS

The biggest differences between HNIRS and HIRS and found in the within-year discharge distribution (and so this only affects the within-year storage amplitudes rather than the over-year storage amplitudes). HIRS is only applied for the American reservoirs. Depending on their relative size, most reservoirs show some kind of storage peaks. This indicates that some parts of the year there is more water demand than other parts of the year. HNIRS totally neglects these within-year water demand fluctuation, but HIRS offers the possibility to define periods with high water demands. In many cases, the discharge simulation significantly improves if water demand is added to the reservoir simulation formula (e.g. in the cases of Bull Lake, Seminoe and Blue Mesa reservoir). Flows in high flow periods are increased and flows in low flow periods are decreased. In case of Lake Powell the discharge simulation is actually decreased. Water is released more or less equally during the year.

As over-year simulations are not really affected if HIRS is applied rather than HNIRS (both models use the same correction for over-year storage fluctuations), only within-year simulation changes appear. In some cases this simulation increases in performance (e.g. for Seminoe reservoir), but this is not always the case (e.g. for Flaming Gorge reservoir).

DVRS

DVRS is actually calibrated on the models used in this method comparison and therefore it needs to be considered that results are not fully objective. Results from the model validated on other reservoirs are not yet available unfortunately.

DVRS seems to perform well in terms of discharge simulation for reservoirs that obviously decrease peak discharges and increase low flows, but not for reservoirs that disturb the complete hydrological behaviour of the system like Lake Powell, Chardara and Toktogul reservoir. Further it seems that reservoirs with big seasonal differences for reservoir inflow are sensitive for this model. For example Nurek reservoir shows a significant decrease of the reservoir outflow in times of high inflow and an increase in times low inflow, but the right order of magnitude of flows is not obtained. Furthermore it seems that reservoir outflow for American reservoirs is often in the right order of magnitude but the timing of the peaks is often estimated (slightly) too early (e.g. for Blue Mesa reservoir). This may indicate that next to reservoir inflows, one also needs to take into account reservoir storage to calculate reservoir outflow.

In terms of storage simulation DVRS often performs well, especially in terms of over-year storage simulations for reservoirs that have to deal with this aspect (e.g. Lake Powell, Toktogul and Andizhan reservoir). In comparison with HNIRS and HIRS, DVRS needs more data about the range of possible storage fluctuations which is not similar to the active storage capacity. If the storage graphs of Canyon Ferry reservoir are considered, it seems that DVRS gives a better representation of the storage fluctuations than HNIRS and HIRS do. For Bull Lake reservoir, the over-year storage is simulated completely wrong. Probably it is a mistake with the plus/minus sign. It seems that over-year storage increases in times that DVRS decreases the over-year storage and the other way around as well.

Table 19: visual inspection results of outflow and storage graphs. ‘yes’ means that results are visually relatively acceptable to acceptable, ‘no’ means that results are visually unacceptable, n.a. means that the model scheme is not tested for a particular reservoir

	Canyon Ferry					Lake Elwell					Bull Lake					Seminoe				
	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS
Height of high outflow peaks	yes	no	no	no	yes	yes	no	no	no	yes	no	yes	no	yes	no	yes	no	no	yes	yes
Timing of high outflow peaks	yes	no	no	yes	yes	yes	no	no	no	yes	yes	no	no	yes	no	yes	no	no	yes	yes
Low flow periods	yes	no	no	no	yes	yes	no	yes	yes	yes	no	no	no	no	no	yes	no	no	yes	yes
Within-year storage fluctuation range	yes	no	no	no	yes	yes	no	yes	yes	yes	no	no	no	no	yes	yes	no	no	yes	yes
Over-year storage fluctuations	yes	no	no	no	yes	yes	no	yes	yes	no	no	no	yes	yes	no	no	no	yes	yes	no

	Flaming Gorge					Blue Mesa					Lake Powell					Tyuyamuyun				
	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS
Height of high outflow peaks	no	no	no	no	yes	yes	no	no	yes	yes	no	no	yes	no	no	yes	yes	yes	n.a.	yes
Timing of high outflow peaks	no	no	no	no	yes	yes	no	yes	yes	no	no	no	no	no	no	yes	no	yes	n.a.	yes
Low flow periods	yes	no	no	yes	yes	yes	no	no	yes	yes	no	no	yes	no	yes	yes	no	yes	n.a.	yes
Within-year storage fluctuation range	yes	no	yes	no	yes	yes	no	yes	yes	yes	yes	no	yes	yes	yes	no	no	no	n.a.	no
Over-year storage fluctuations	no	no	no	no	yes	no	no	yes	yes	no	no	no	yes	no	yes	no	no	no	n.a.	no

	Nurek					Kayrakkum					Andizhan					Charvak				
	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS
Height of high outflow peaks	no	no	no	n.a.	yes	yes	no	yes	n.a.	yes	yes	yes	no	n.a.	no	yes	yes	yes	n.a.	yes
Timing of high outflow peaks	no	no	yes	n.a.	yes	yes	no	yes	n.a.	yes	yes	no	yes	n.a.	yes	yes	no	yes	n.a.	yes
Low flow periods	no	no	no	n.a.	yes	no	no	no	n.a.	yes	no	no	no	n.a.	no	no	no	yes	n.a.	yes
Within-year storage fluctuation range	no	yes	no	n.a.	no	no	yes	no	n.a.	yes	yes	no	no	n.a.	no	no	yes	no	n.a.	yes
Over-year storage fluctuations	yes	yes	yes	n.a.	yes	no	yes	yes	n.a.	no	no	no	yes	n.a.	yes	yes	yes	no	n.a.	yes

	Chardara					Toktogul					Tuyen Quang					Angat				
	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS	NLOS	SWAT	HNIRS	HIRS	DVRS
Height of high outflow peaks	no	no	no	n.a.	no	yes	no	no	n.a.	no	yes	no	yes	n.a.	yes	yes	yes	yes	n.a.	yes
Timing of high outflow peaks	no	no	no	n.a.	no	no	no	no	n.a.	no	yes	no	yes	n.a.	yes	yes	no	yes	n.a.	yes
Low flow periods	no	no	no	n.a.	yes	no	no	no	n.a.	no	yes	no	yes	n.a.	yes	yes	no	yes	n.a.	yes
Within-year storage fluctuation range	no	yes	no	n.a.	yes	yes	yes	yes	n.a.	yes	yes	yes	yes	n.a.	yes	yes	no	no	n.a.	yes
Over-year storage fluctuations	yes	yes	no	n.a.	yes	no	no	yes	n.a.	yes	no	no	yes	n.a.	no	no	no	no	n.a.	yes

7 Discussion

This chapter will discuss the study approach. First the strengths and weaknesses of the used methods will be discussed during a review of the followed method. After that a comparison is made between results obtained in this study and in several other studies. Hereafter some suggestions will be given about steps that could be taken how to proceed further with this topic of reservoir simulations.

7.1 Review of followed method

For this study there was very little data available that could be effectively used in achieving our goal to explain how reservoir operations should be modelled by using a combination of easy-to-obtain reservoir data and a river basin hydrological model. This is considered as a weakness of this study, but at the same time as a strength. It is a weakness because a small amount of data provides no hard evidence that proposed relationships are as they are. On the other hand, it is also visible that relations proposed by others (e.g. the inflow dependency relationship for reservoirs with *IR* < 0.5y by Hanasaki et al. (2006) are not valid for this study's sample of reservoirs, see section 5.2.2. It also shows that there is still not a lot of easy-to-obtain data available that may be beneficial for worldwide reservoir simulations. The importance of thorough insight in water resources management of reservoirs is therefore demonstrated as data that describes reservoir systems is generally not available. Some important examples of data that was only limited available during this study:

- There was only time series data used for sixteen reservoirs on the world. Operational relations for DVRS are drawn from only this sample of sixteen reservoirs, which were even located on just two continents. Four complete reservoir containing continents are entirely overlooked during the establishment of operational relations and testing of other models. Even for the two continents where data was available the reservoirs were only located in three or four geographic areas making the reservoirs not even representative examples for the entire continent.
- There were no river basin scale hydrological models used that simulated reservoir inflow on a daily time step. One consequence of this is that instead of simulated reservoir inflow the observed reservoir inflows are used. The observed inflows are actually not always observed but often calculated from the reservoir water balance. Outflows and storage changes are measured and added to a water balance. The residual term is often simplified as reservoir inflow, meaning that reservoir evaporation and leakage are not taken into account or simplified. It is hard to give an indication how accurate this 'observed' reservoir inflow is or if it is even more representative for real inflow than if reservoir inflows from a hydrological model are used. The fact that no simulated reservoir inflows are used could have a significant effect on error propagation in a hydrological/water resources model.
- Water demand data and operational rules were hardly available. There are reservoir simulation models that need the user to define water demand and operational rules that have an effect on reservoir outflow simulation that are not tested in this study (e.g. WEAP, HEC-ResSim and the schemes developed by Haddeland et al. (2006) and Wu & Chen (2012)). Since reservoirs have often multiple purposes and not every purpose is as important as the others, defining water demand is very difficult. Therefore it was only possible to apply our method to a small selection of reservoir simulation models, simply because of the fact that formula terms involving water demand or operational rules could not be filled in. Only one model (HIRS) had

a simple water demand module for which reasonable assumptions regarding water demand could be made.

A strength of the followed method is that it is one of the first studies known to date that compares the results of multiple reservoir simulation models with each other without incorporating local knowledge (e.g. by calibrating model parameters on available local parameters or by having insight in local water resources management). Water resource modellers are not always known with the water resources system of a particular area and thus customizing reservoir simulation models to the behaviour of reservoir operators in a certain area is not always easy. The outcomes of this study are fully the result of the original designed reservoir simulation schemes and are not adapted to local conditions such as in studies by Biemans et al. (2011) and Voisin et al. (2013) who modify the original scheme of Hanasaki et al. (2006) for a certain area. Even for DVRS, operational relations are as much as possible drawn without looking at the areas where the reservoirs used for drawing the operational relations are located in. Of course it must be said that all tested schemes will work better if more knowledge about the operational rules of reservoirs is available.

Another weakness is perhaps the assessment of the results. Since all methods show a weak performance for all reservoirs in terms of NRMSE and r^2, an assessment based on visual inspections on the results was performed. This visual inspection was only performed by the author of this thesis what makes the results very subjective. It is hard to make an assessment of a visual inspection in a more objective way. Probably this would be possible if multiple experts in hydrology do this assessment as well, since they have expertise about when results can be considered as weak or strong. The downside of this method is that it is a time consuming process and the results remain subjective results in a certain degree.

7.2 Comparison of results with other studies

As already noticed in section 7.1, this study is one of the first studies known to date that compares results of multiple simulation models with each other without incorporating local knowledge. One study that does compare multiple original reservoir schemes is performed by Hanasaki et al. (2006). The reservoir models compared include either HIRS or HNIRS (dependent on the reservoir purpose: irrigation or non-irrigation) and NLOS. Further these reservoir models are compared with taking Q_{in} as a proxy for outflow and taking $Q_{in,avg}$ as a proxy for outflow. Results are only assessed based on NRMSE but not by visual inspection as is done in this study. It seemed that for non-irrigation reservoirs, the NRMSE of HNIRS was the lowest for 11 out of 18 tested reservoirs. For irrigation reservoirs, it seems that the NRMSE of HIRS was the lowest for 7 out of 10 reservoirs. It has to be said that for these irrigation reservoirs there was water demand data available. The model performance of HNIRS and HIRS in terms of outflow simulation seems to be significantly better for the reservoirs tested there compared with the performance of HNIRS and HIRS in this study, where in terms of NRMSE HNIRS and HIRS are the best for only 3 out of 16 reservoirs. Probably this is the result of assessing different reservoirs in either studies or the result of different assessment dates. In this study, the assessment years were 2002 – 2009 for 14 out of 16 reservoirs and the time resolution for assessment was a day, but in the study of Hanasaki et al. (2006) the assessment years were earlier in time and the time resolution for assessment was a month. This makes the outcomes of both studies hard to compare. At least it can be said that for more objective comparisons of reservoir simulation schemes they should be tested for significantly more reservoirs around the world spread in significantly different climatic zones.

In the quest for more studies that applied one or more of the tested reservoir simulation schemes, one study was found where a hydrological model in SWAT was made for a catchment in North Africa including two reservoirs (Bouraoui et al. 2005). It was however decided not to use the SWAT reservoir simulation tool because of a lack of information regarding management (storage, release and distribution). This indicates that applying SWAT to this modelling problem where hardly any data is available would not lead to the desired results.

As becomes clear after reading the discussion so far, not many studies took the opportunity yet to compare reservoir simulation models with each other that are non data-driven. Therefore this research should encourage researchers to continue with this topic to compare reservoir simulation models with each other for many types of reservoirs in many climatic zones of the world. This is considered to be difficult. Data owners should become more aware that sharing their data will eventually lead to better insights in reservoir operations around the world.

7.3 Further research and parallel developments

Because this study only uses a limited amount of data, further research is needed that uses the same approach to come up with more informed results. As already noticed in section 7.1, more data is necessary to achieve this. First, more reservoir time series of multiple reservoir types spread over the world in various climatic zones are necessary in order to compare the methods for multiple situations. On this way, one can better check if there are similarities between operational rules of reservoirs. A second step is that reservoir modules tested here should all be built in a hydrological/water resources model to test the performance if simulated reservoir inflow is used rather than observed reservoir inflow. An additional advantage of building in all reservoir simulation models is that error propagation analyses can be performed for reservoirs which are connected in series. Thirdly, a better representation of water demand data for reservoirs is necessary so that other models that need water demand to be defined can also be subjected to a comparison. On this way hopefully even more knowledge on simulations of reservoir operations can be obtained than is done after performing this study.

The DVRS model developed in this study also needs to be further investigated. The outflow ratio r that determines the outflow as a fixed percentage of inflow in months that inflow is generally above yearly average is now only dependent on the impoundment ratio *IR*. Taking into account the coefficient of variation of inflow C_v (Vogel et al. 1999) should also be beneficial for determining the outflow ratio r, since it is more likely that inflows with high coefficients of variation will be decreased more in times of above average inflows than inflows with low coefficients of variation will do. If a better representation of water demand data for reservoirs comes available, perhaps that can be included as well in the DVRS model.

The over-year scheme of the DVRS model developed in this study shows now already potential to be useful in situations that future water resources needs to be assessed. For example, a study by Barnett & Pierce (2008) tries to emphasize that Lake Mead and Lake Powell have a chance of 50% to turn dry in 2021, which is based on climate projections and the current hydrological scheme. Projected SPEI values on the time scale used in this study until 2021 could be created by using the same climate projections as used by Barnett & Pierce. The outcome will possibly be a reservoir storage that will indeed drop till approximately the bottom of the reservoir.

Next to a non-data driven approach to simulate reservoir operations, there are also data driven approaches in development that can simulate reservoir operations in a far more accurate way than is done in this study. Some key examples of studies that use fuzzy logic and/or artificial neural networks in order to train a reservoir simulation model are performed by Chang & Chang (2006) and Mousavi et al. (2007). Historical observed combinations of reservoir inflow, storage and outflow (and possibly also other variables) are used to train a model. In case that two (or more) variables are known, for example reservoir inflow and storage, the model gives a solution for the reservoir outflow based on the trained dataset. In order to do so, a lot of historical time series data is necessary.

As said earlier in this chapter, more information on operations of more reservoirs is necessary before one can check if there are similarities between operations rules of reservoirs. Since reservoir data is often considered as sensitive and not often freely available (Gao et al. 2012), there is a possibility that remote sensing products can contribute to this topic. Recent developments in remote sensing techniques can in theory contribute significantly. Partly remotely sensed rainfall products may be beneficial as forcing in models in order to simulate acceptable reservoir inflows for example. A very popular example is the Tropical Rainfall Measuring Mission, a joint space mission between NASA and JAXA. Several studies use TRMM data for daily modelling purposes (e.g. Collischonn et al. 2008; Terink & Droogers 2014) leading to acceptable results. Also hydrological models that can effectively deal with remotely sensed data are in development (e.g. Terink et al. (2014)). Besides being beneficial for simulation of reservoir inflow, remotely sensed methods can also be useful to determine storage and storage fluctuations. Recent research shows that it is possible to approximate the quality and usefulness of in-situ data of reservoirs by using satellite imagery data, a Digital Elevation Model (DEM), altimetry data or a combination of those (Åström 2011; Duan & Bastiaanssen 2013).

8 Conclusions and recommendations

This study provided an overview how different available hydrological/water resources models take reservoir operations into account and how well they perform for sixteen case studies, provided that necessary data was easily available or reasonable assumptions could be made. It also showed how easy-to-obtain datasets and reservoir properties can contribute to the simulation of reservoir operations. Furthermore the study tried to show what type of reservoir simulation model should be applied for a certain reservoir type. Generally it was difficult to find data for reservoirs around the world, except for reservoirs in the western half of the United States of America. Furthermore, data from some particular locations in Asia was available as well. For this reason, conclusions will not be world covering. The conclusions are particularly meant as a lesson for hydrologists and water resources modellers, who are interested in simulation of reservoirs, on how well individual reservoirs can be modelled by using a combination of available reservoir simulation methods and easy-to-obtain data if no local reservoir operational rules, water demand data or long historical time series are available. The following conclusions and recommendations can be drawn from this research:

1. How do several existing (hydrological) models take reservoir operations into account for several types of reservoirs and how well do they perform and for which data investment?
    - Neitsch et al. 2002 (SWAT)
        - makes use of a target storage release approach between a maximum and minimum defined storage to simulate reservoir outflow, inclusion of upstream soil wetness is possible
        - performance is only sufficient for within-year reservoirs with annually recurring storage patterns in terms of storage simulation, results for other cases are generally poor in terms of outflow and storage simulation
        - necessary data is easy to obtain and physically measurable except for the parameter ND_{targ} which is difficult to estimate or calibration is necessary, water demand is not taken into account
        - variations on this reservoir simulation model include more unmeasurable parameters which have to be estimated or calibrated
    - Hanasaki et al. 2006 (HNIRS and HIRS)
        - makes use of actual inflow, long term averaged inflow, impoundment ratio and storage at the beginning of the operational year to simulate reservoir outflow, inclusion of water demand is relatively easy
        - overestimates outflow in high flow periods and underestimates outflow in low flow periods for tested reservoirs with small impoundment ratios, does not simulate within-year outflow fluctuations for reservoirs with large impoundment ratios if no water demand is defined, storage simulations are often sufficient
        - necessary data is easy to obtain and physically measurable, definition of water demand data is optional and is defined as a proportion of the total demand over the year, so exact water demand values are not necessary
        - variations on this reservoir simulation model include site specific knowledge on temporal distribution of outflow and definition changes of water demand
    - Haddeland et al. 2006

- makes use of a combination of four objective functions for four possible reservoir purposes which need to be optimized for outflow depending on the importance of each reservoir purpose
- performance is not tested, because importance of reservoir purposes was unknown for every reservoir, further assumptions needed to be done that were open to the interpretation of the modeller or parameters needed to be calibrated on historical observations or filled in provided that operational rules were known
- local operational rules are necessary to apply this reservoir scheme, some parameters are open for own interpretation
- variations on this reservoir simulation model include site specific knowledge and more assumptions open to the interpretation of the modeller

- Wisser et al. 2010
    - dependent on the actual inflow, outflow is calculated by one out of two formulas that uses actual inflow and long term averaged inflow as input variables
    - performance is not tested because of its over simplicity, all reservoirs are modelled on the same way
    - necessary data is easy-to-obtain and physically measurable
    - no variations are known to date
- Yates et al. 2005 (WEAP)
    - makes use of a combination of individual reservoir operational rules and four user defined operational storage zones, if storage drops or rises to a certain storage zone the outflow according to predefined operational rules is increased or decreased according to the rules of that particular zone
    - performance is not tested, because individual reservoir operation rules are not known
    - local operational rules and definition of four operational storage zones are necessary to apply this reservoir scheme
    - no variations known to date
- Döll et al. 2003 (NLOS)
    - treats reservoirs as natural lakes, outflow is only dependent on actual storage and total active storage
    - performance is sufficient in terms of discharge for many American reservoirs that show high outflows in times that reservoirs are full, performance is insufficient for many reservoirs in terms of (over-year) storage simulation
    - necessary data is easy-to-obtain and physically measurable
    - no variations known to date
- HEC-ResSim
    - makes use of many individual reservoir properties and reservoir operational rules
    - performance is not tested, because individual reservoir operation rules are not known and many reservoir properties as well

- local operational rules are necessary to apply this reservoir scheme, together with many individual reservoir properties
- no variations known to date

2. How can different easy-to-obtain datasets and reservoir properties be beneficial for the simulation of reservoir operations?
   - The impoundment ratio of a reservoir is an informative reservoir property that is useful if a reservoir is supply driven. Supply driven reservoirs are often reservoirs with small impoundment ratios. Reservoirs with small impoundment ratios spill a large majority of their inflows immediately after the water enters the reservoir. The reservoir has only relatively little storage capacity, so reservoir inflow cannot be stored for a long time.
   - The Standardized Precipitation Evapotranspiration Index (SPEI) is useful in order to simulate over-year storage fluctuations. If a reservoir shows over-year storage fluctuations, the storage patterns could almost always be sufficiently reproduced by the SPEI, the average and the standard deviation of the storage (assumed that reservoir storage patterns are normally distributed). Although it is especially the longer SPEI time scales that show good correlations with reservoir storage fluctuations for reservoirs with relatively large impoundment ratios, there seems to be no direct relation between the impoundment ratio and the optimal SPEI time scale.
   - Easy-to-obtain datasets such as the SPEI and reservoir properties such as the impoundment ratio can be combined to create a new reservoir simulation model (DVRS). This model seems to perform sufficiently for many of the sixteen tested reservoirs. It must be said however that the DVRS model is not validated for reservoirs that were not involved in the design process of the DVRS model. Therefore it is advised to test the model performance of DVRS for other reservoirs in further research.
   - The effect of the coefficient of variation C_v of reservoir inflow on reservoir behaviour needs to be assessed in further research. This may be a useful reservoir property as well.
3. Which types of reservoir simulation models should be applied for which combination(s) of reservoir properties and climatic properties for the area where the reservoir is located in?
   - It is difficult to classify classes of reservoirs with the same reservoir properties and climatic properties for the area where the reservoir is located in. Even if reservoirs have the same impoundment ratio and are located in the same area, it does not always mean that a particular reservoir simulation model always gives sufficient results for all reservoirs sharing the same properties. Furthermore there is no model that distinguishes itself by its performance for all tested reservoirs.
   - Over-year American reservoirs tested in this study seem to perform best if NLOS is applied in terms of reservoir outflow simulation. Regarding storage simulation, no compelling results are obtained. DVRS, HNIRS and HIRS seem to perform sufficiently in many cases.
   - For Asian reservoirs that mainly show within-year behaviour, it is often the best decision not to use any of the tested reservoir simulation models. Using actual reservoir inflow as a proxy for outflow often shows best results. Regarding storage

simulation, DVRS shows the best results in terms of within-year storage simulation while DVRS and HNIRS together show the best results in terms of over-year storage simulation.

- More research is necessary to find out what kind of reservoir simulation models are best in several cases. Therefore the following recommendations are made:
    - More time series of multiple reservoir types spread over the world in various climatic zones are necessary in order to compare the methods for multiple situations. On this way, one can check if there are similarities between operational rules of reservoirs.
    - Reservoir modules tested in this study should be built in a hydrological/water resources model to test the performance if simulated reservoir inflows are used rather than observed inflows. Furthermore, this means that error propagation analyses can be performed for reservoirs which are connected in series.
    - More research should be done on the worldwide representation of reservoir water demands. On this way, models that need water demand to be defined can be subjected to a better comparison.

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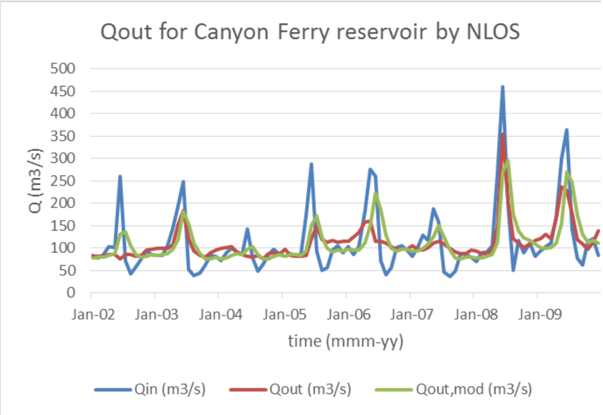
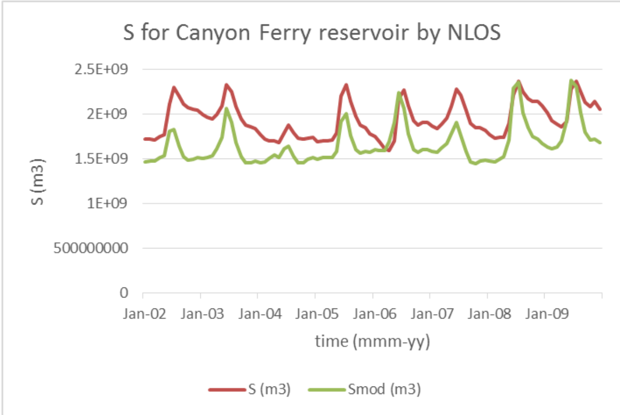
Appendices

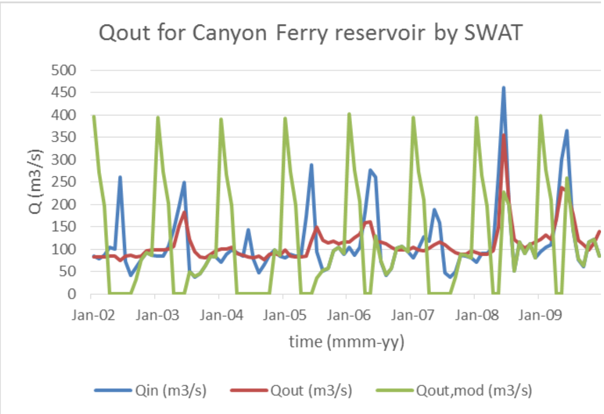
Appendix A

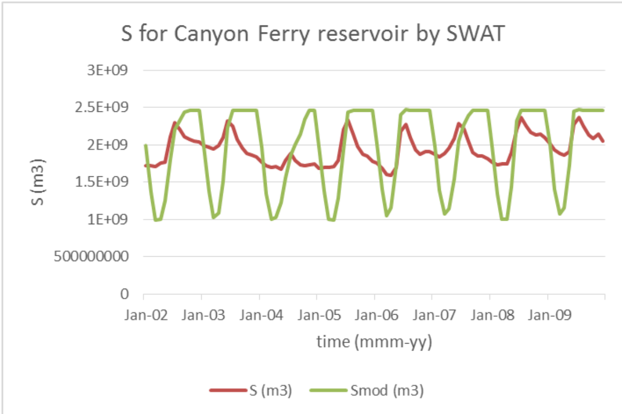
Reservoirs in United States of America

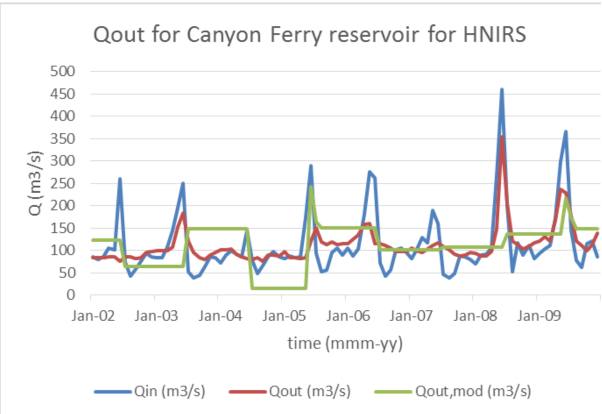
Canyon Ferry

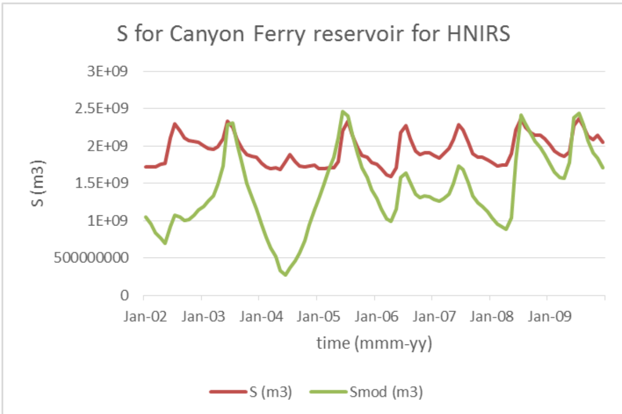


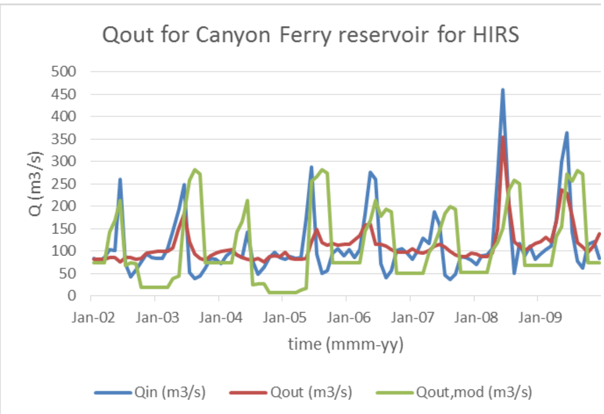


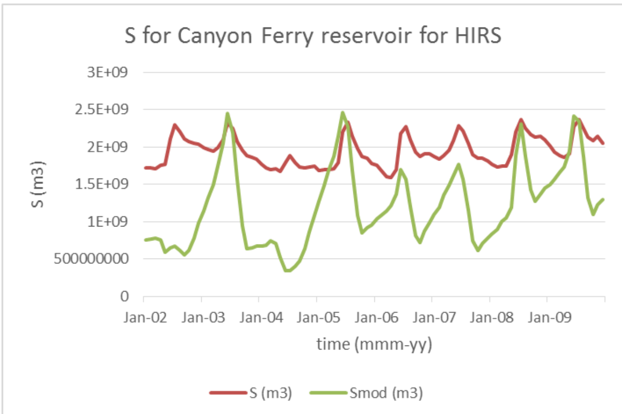


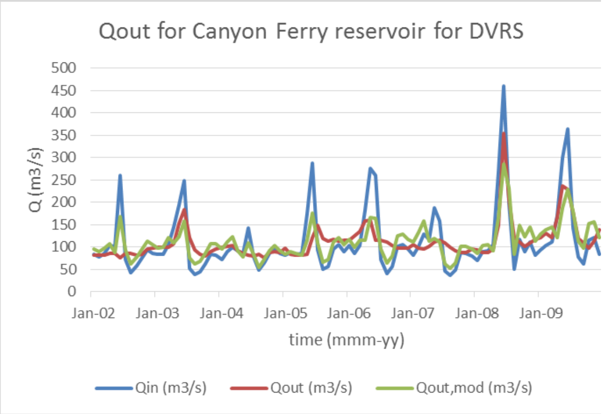




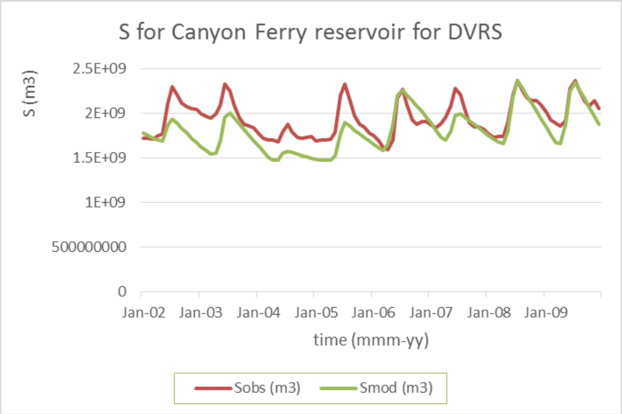






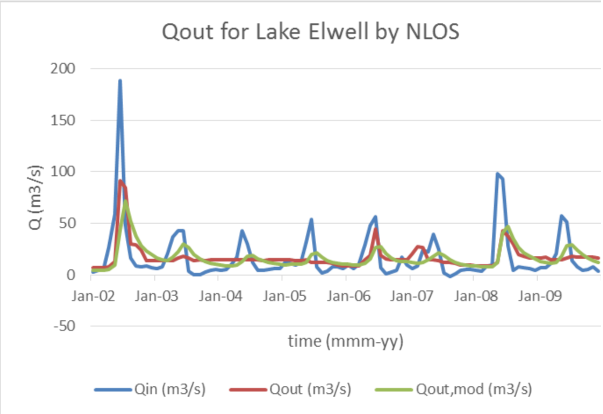


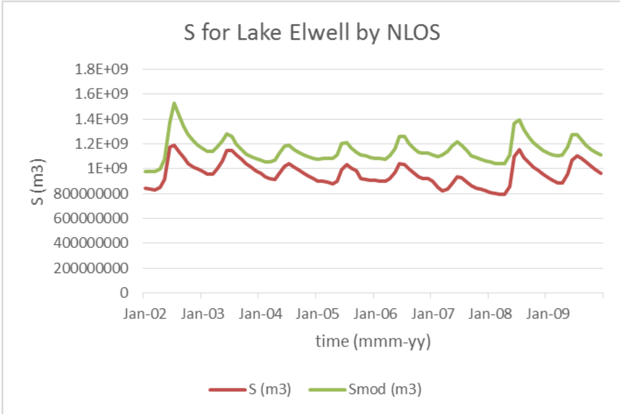
Qout for Canyon Ferry reservoir for DVRS
Q (m3/s)
500
450
400
350
300
250
200
150
100
50
0
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

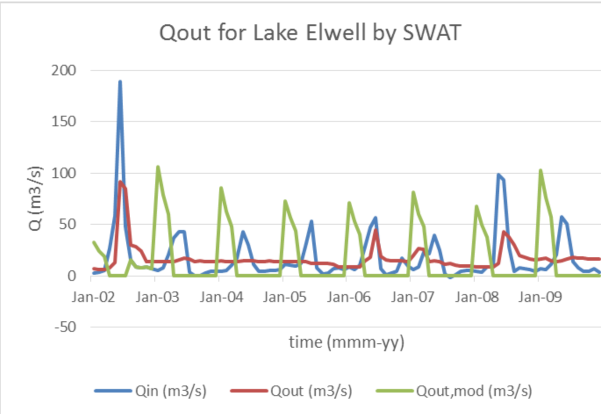


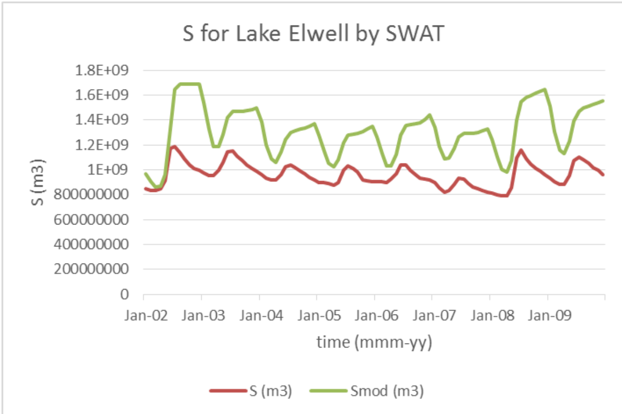
S for Canyon Ferry reservoir for DVRS
S (m3)
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Sobs (m3)
Smod (m3)

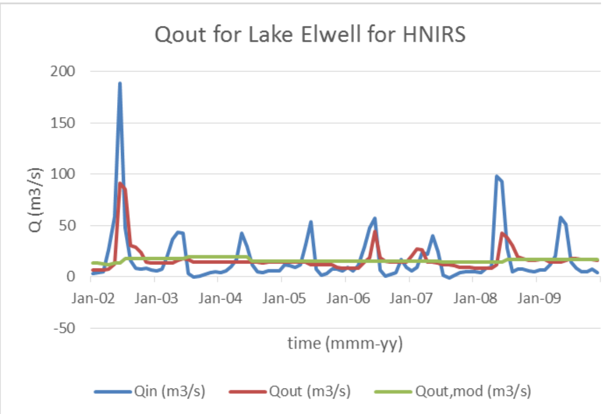
Lake Elwell

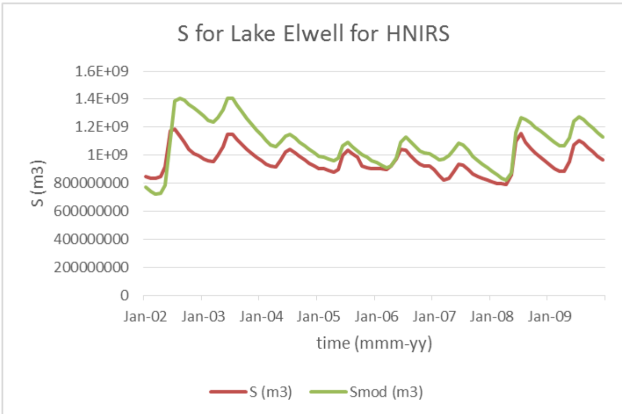

Qout for Lake Elwell by NLOS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

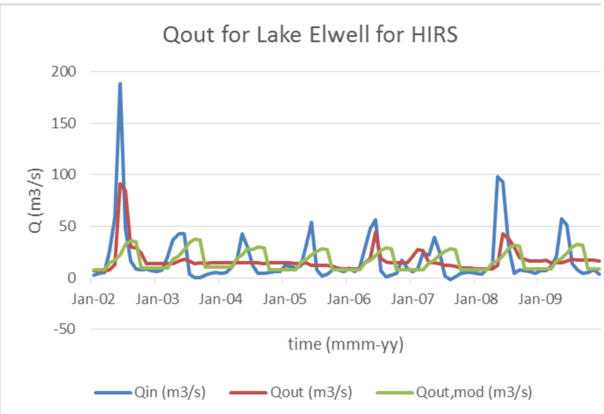

S for Lake Elwell by NLOS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

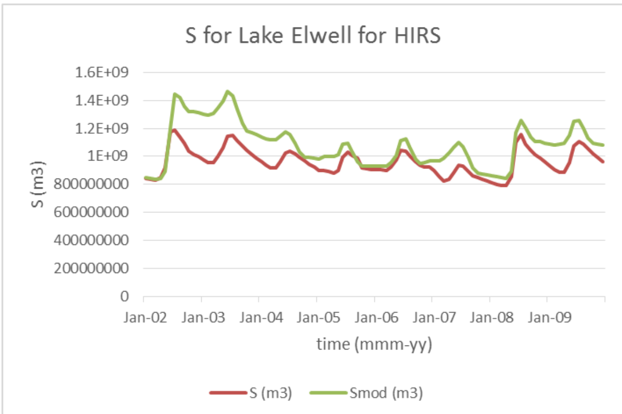

Qout for Lake Elwell by SWAT
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

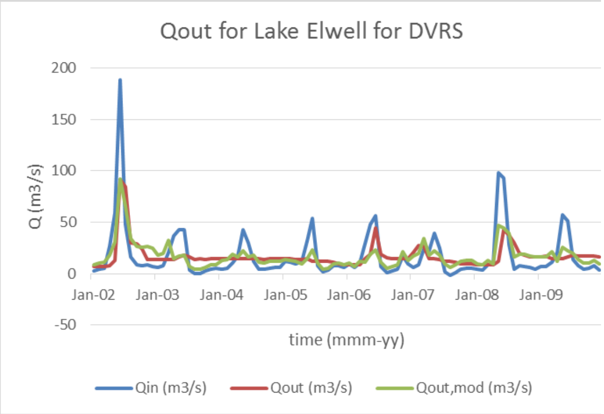

S for Lake Elwell by SWAT
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

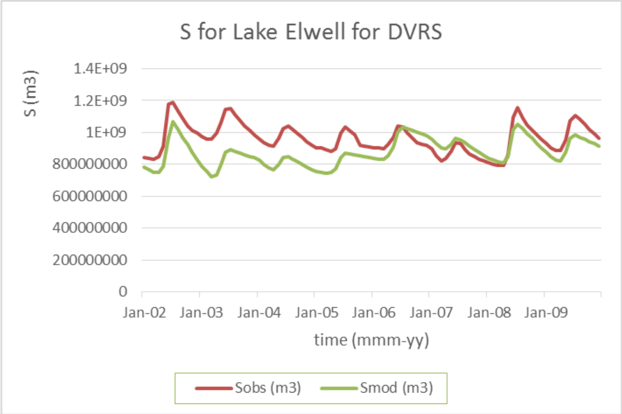

Qout for Lake Elwell for HNIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)


S for Lake Elwell for HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

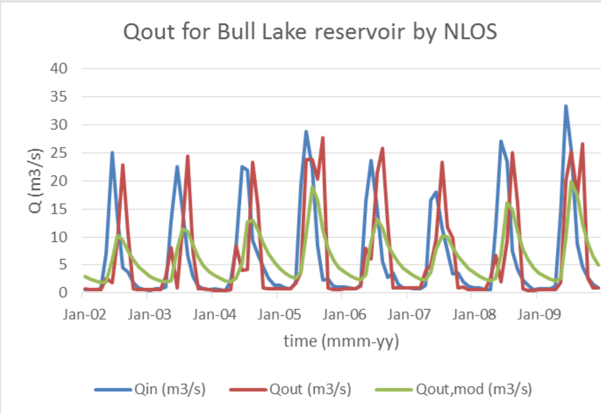

Qout for Lake Elwell for HIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

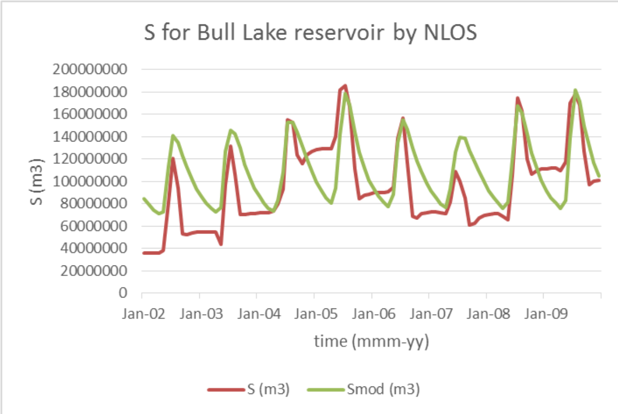

S for Lake Elwell for HIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

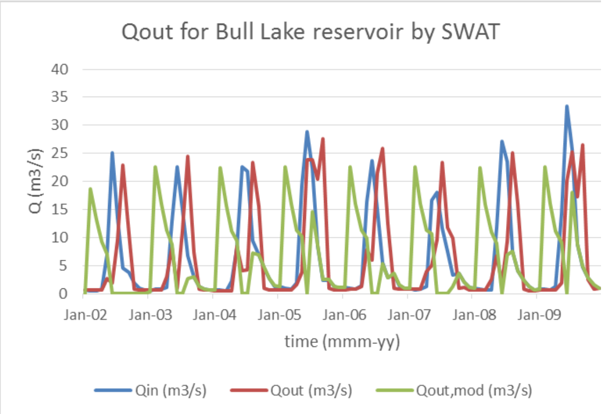

Qout for Lake Elwell for DVRS
200
150
100
50
0
-50
Q (m3/s)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

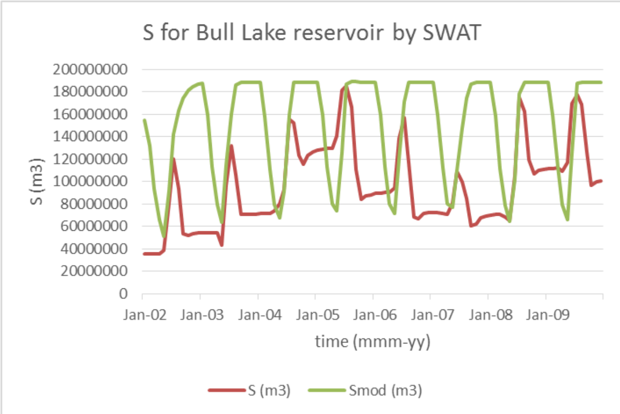

S for Lake Elwell for DVRS
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Sobs (m3)
Smod (m3)

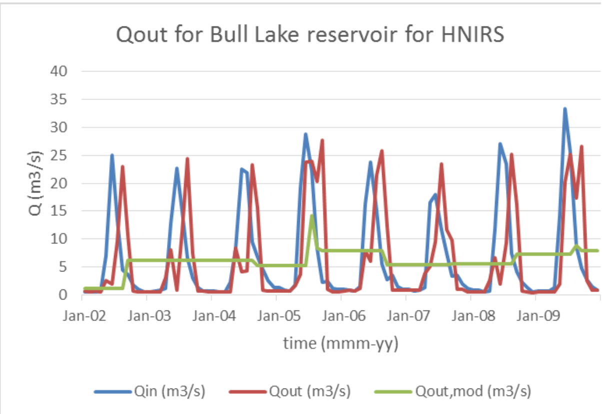
Bull Lake

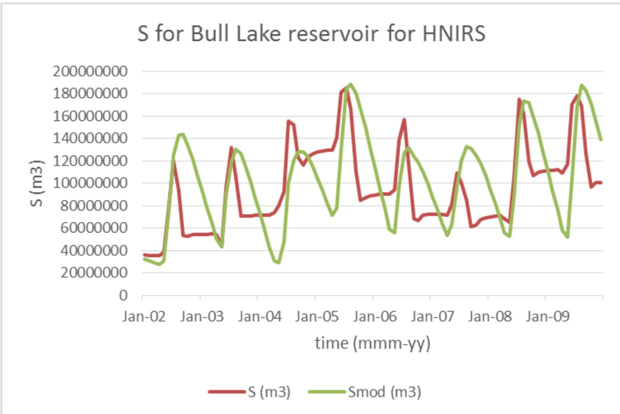

Qout for Bull Lake reservoir by NLOS
Q (m3/s)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

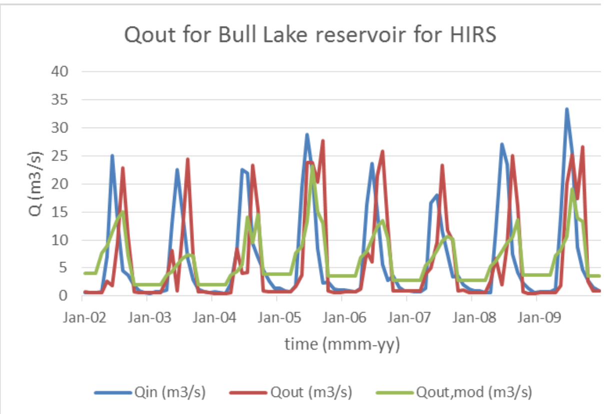

S for Bull Lake reservoir by NLOS
S (m3)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
S (m3)
Smod (m3)

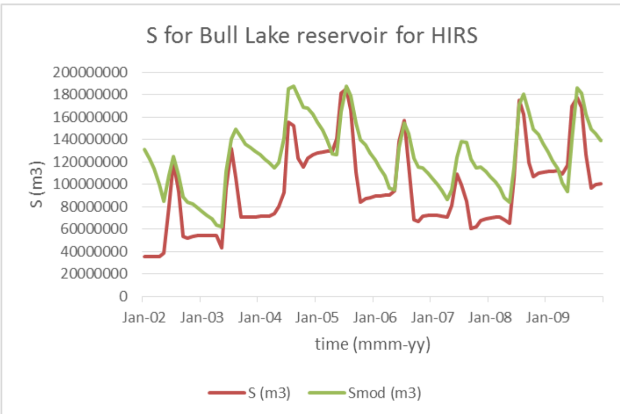

Qout for Bull Lake reservoir by SWAT
Q (m3/s)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

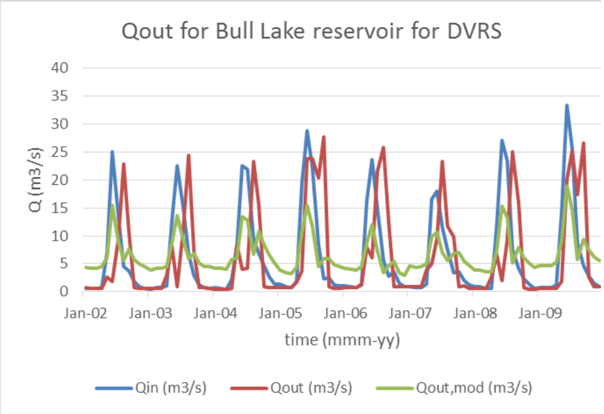

S for Bull Lake reservoir by SWAT
S (m3)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
S (m3)
Smod (m3)

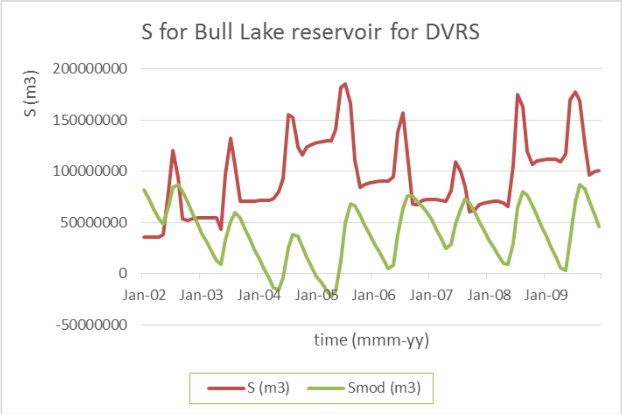

Qout for Bull Lake reservoir for HNIRS
Q (m3/s)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)


S for Bull Lake reservoir for HNIRS
S (m3)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
S (m3)
Smod (m3)

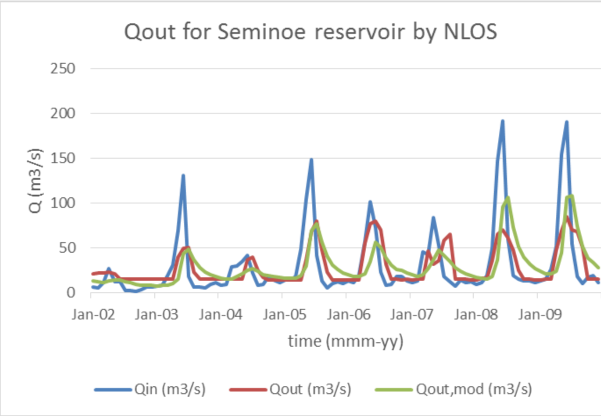

Qout for Bull Lake reservoir for HIRS
Q (m3/s)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

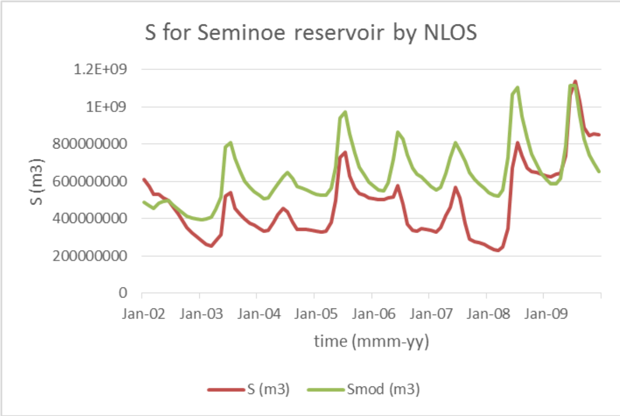

S for Bull Lake reservoir for HIRS
S (m3)
time (mmm-yy)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
S (m3)
Smod (m3)

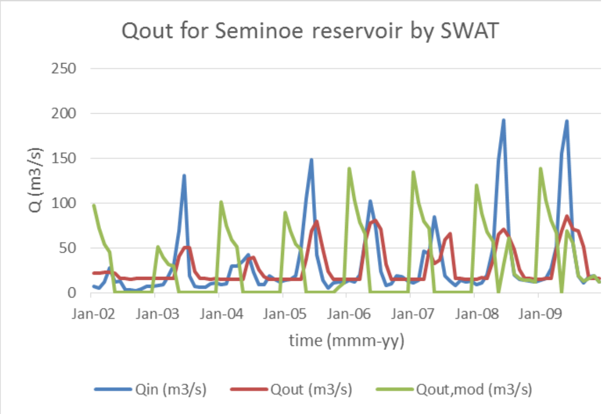

Qout for Bull Lake reservoir for DVRS
Q (m3/s)
40
35
30
25
20
15
10
5
0
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

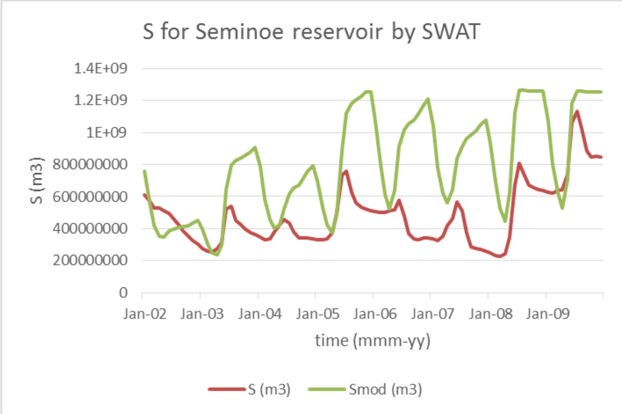

S for Bull Lake reservoir for DVRS
S (m3)
200000000
150000000
100000000
50000000
0
-50000000
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

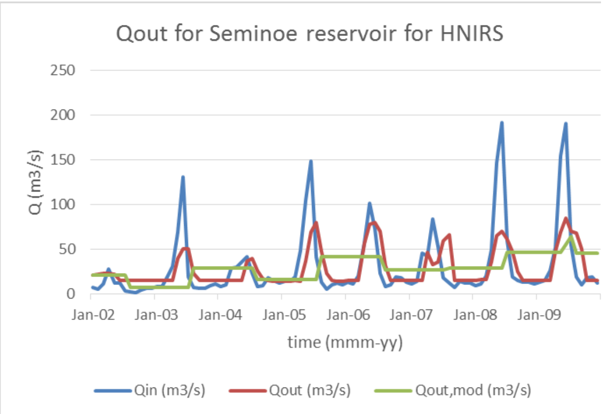
Seminoe

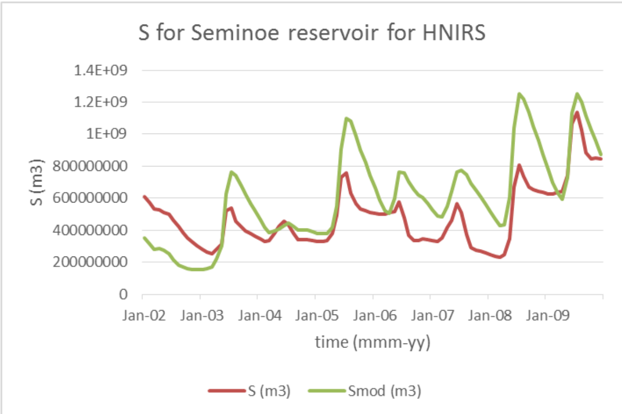

Qout for Seminoe reservoir by NLOS
250
200
150
100
50
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

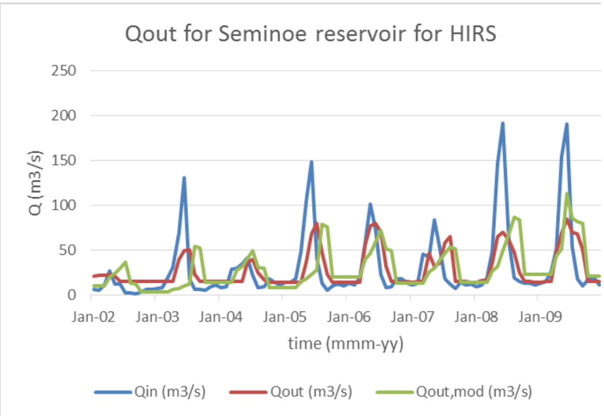

S for Seminoe reservoir by NLOS
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

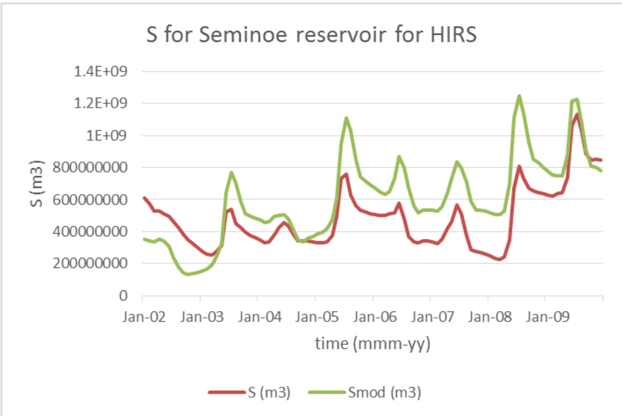

Qout for Seminoe reservoir by SWAT
250
200
150
100
50
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

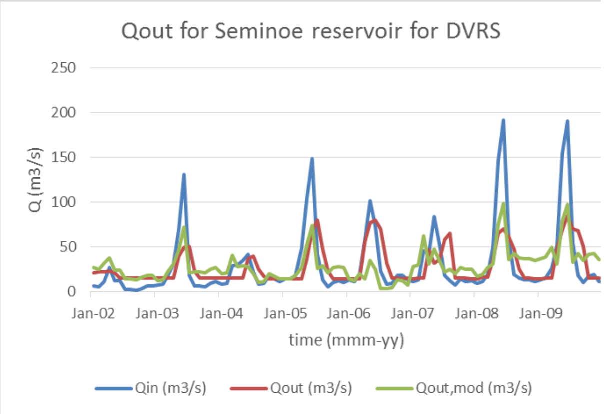

S for Seminoe reservoir by SWAT
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)


Qout for Seminoe reservoir for HNIRS
250
200
150
100
50
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

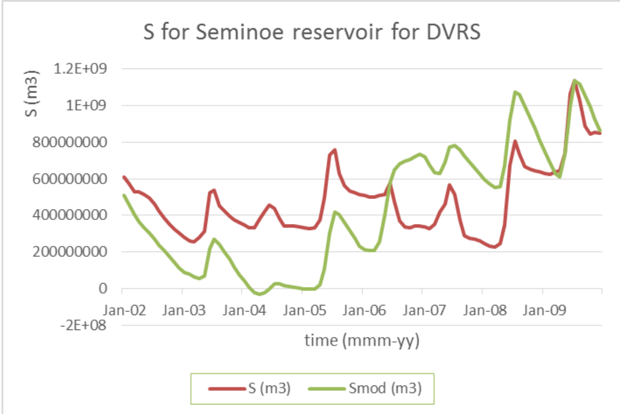

S for Seminoe reservoir for HNIRS
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)


Qout for Seminoe reservoir for HIRS
250
200
150
100
50
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

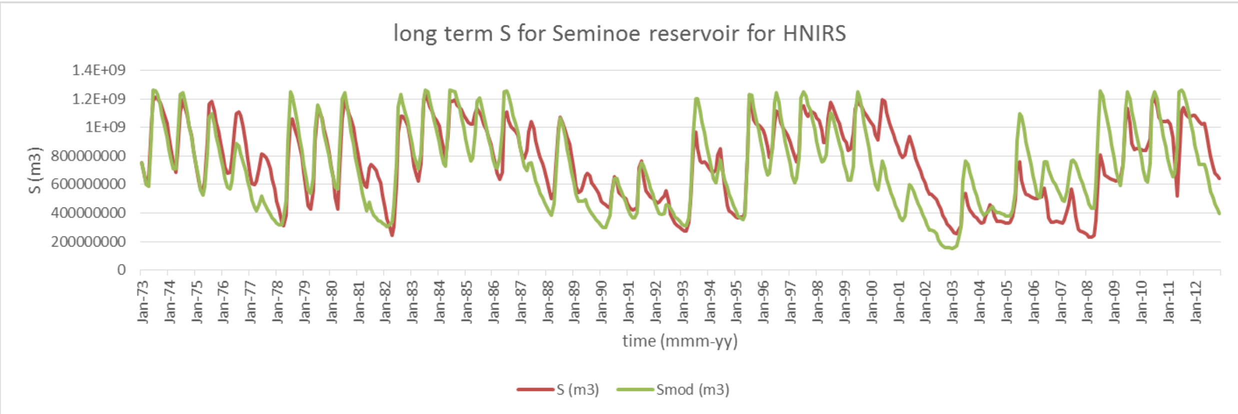

S for Seminoe reservoir for HIRS
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)



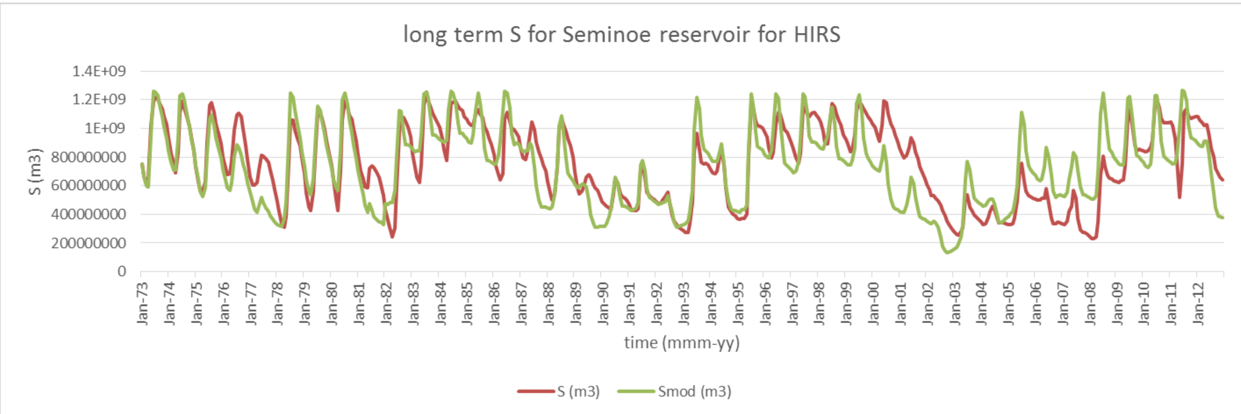
Qout for Seminoe reservoir for DVRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)



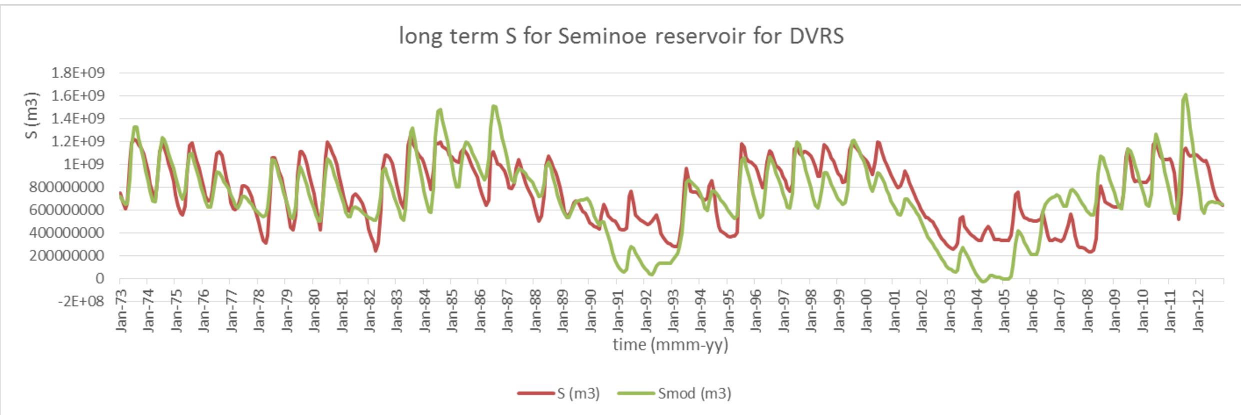
S for Seminoe reservoir for DVRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)



long term S for Seminoe reservoir for HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

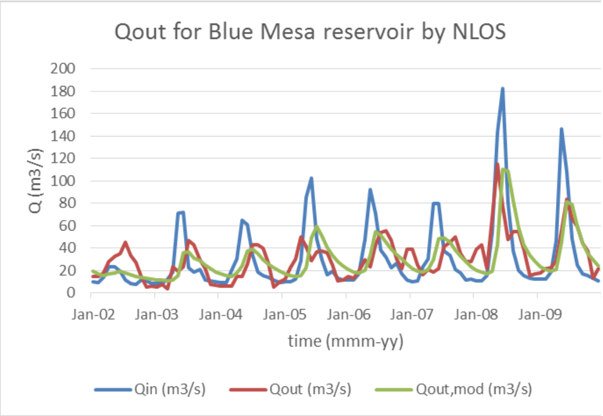


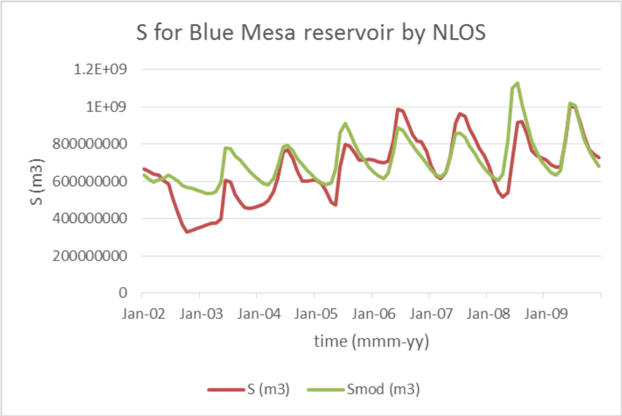
long term S for Seminoe reservoir for HIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

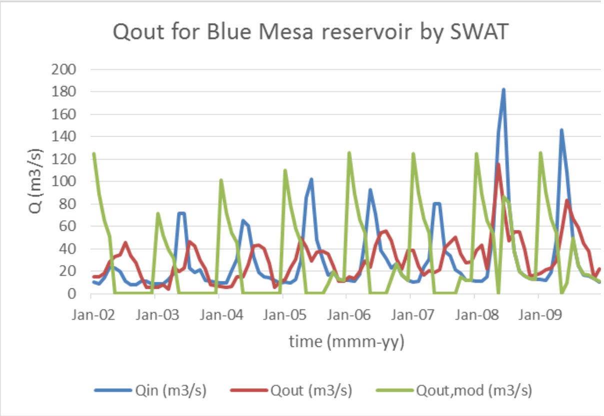


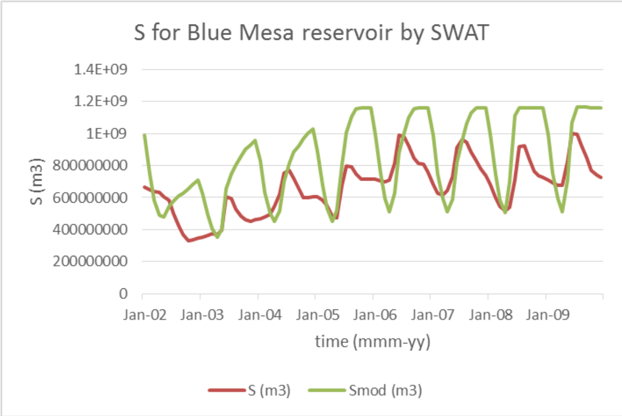
long term S for Seminoe reservoir for DVRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

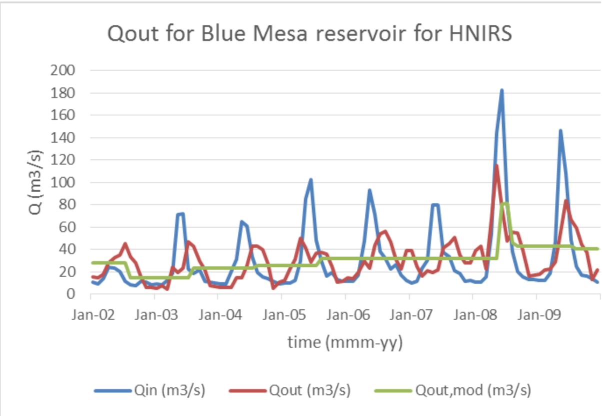
Blue Mesa

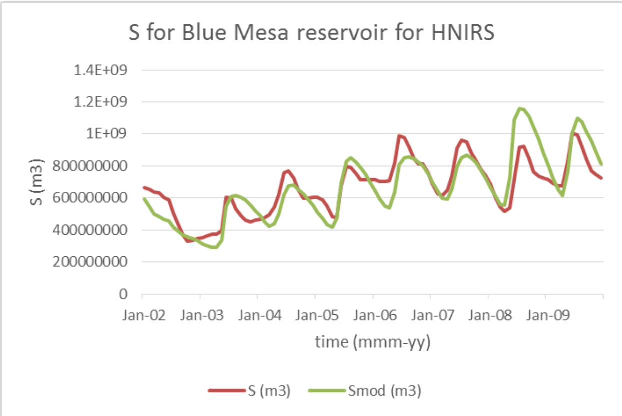

Qout for Blue Mesa reservoir by NLOS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

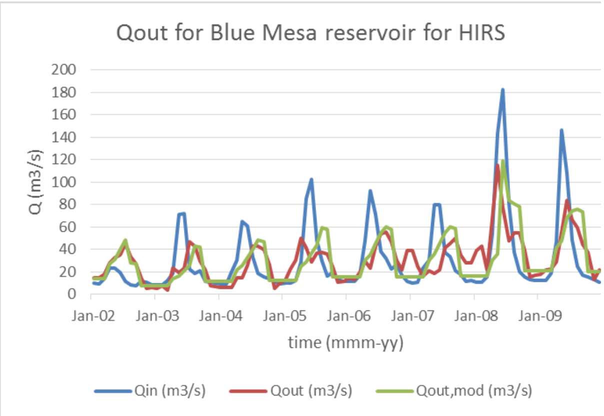

S for Blue Mesa reservoir by NLOS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

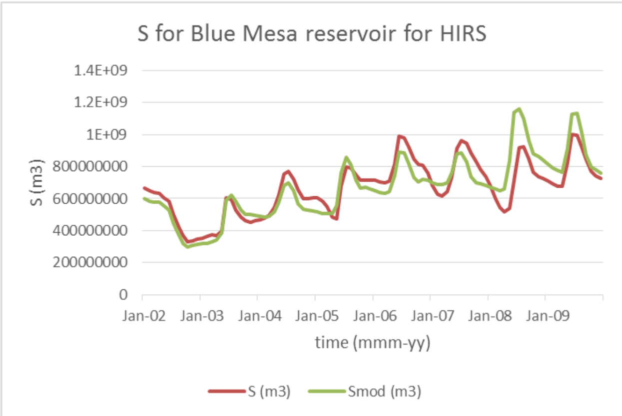

Qout for Blue Mesa reservoir by SWAT
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

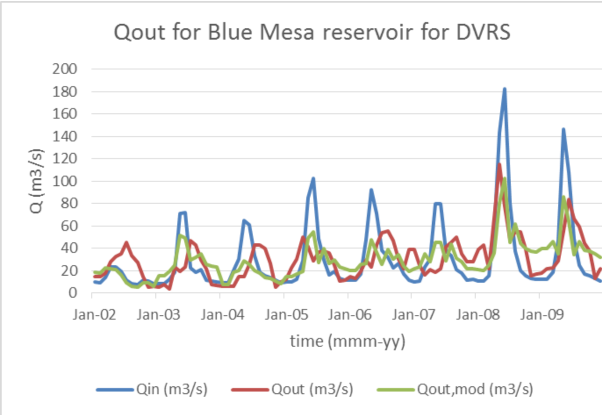

S for Blue Mesa reservoir by SWAT
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

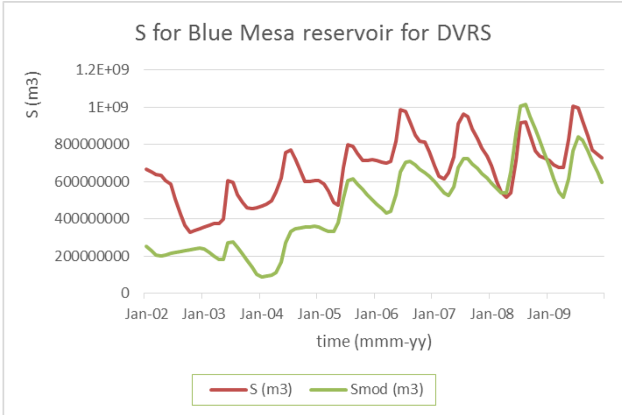

Qout for Blue Mesa reservoir for HNIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

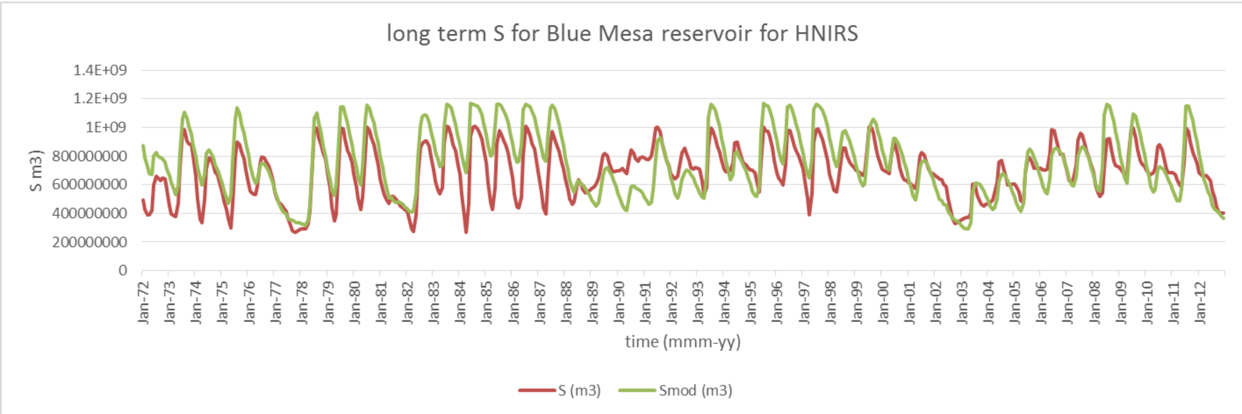

S for Blue Mesa reservoir for HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

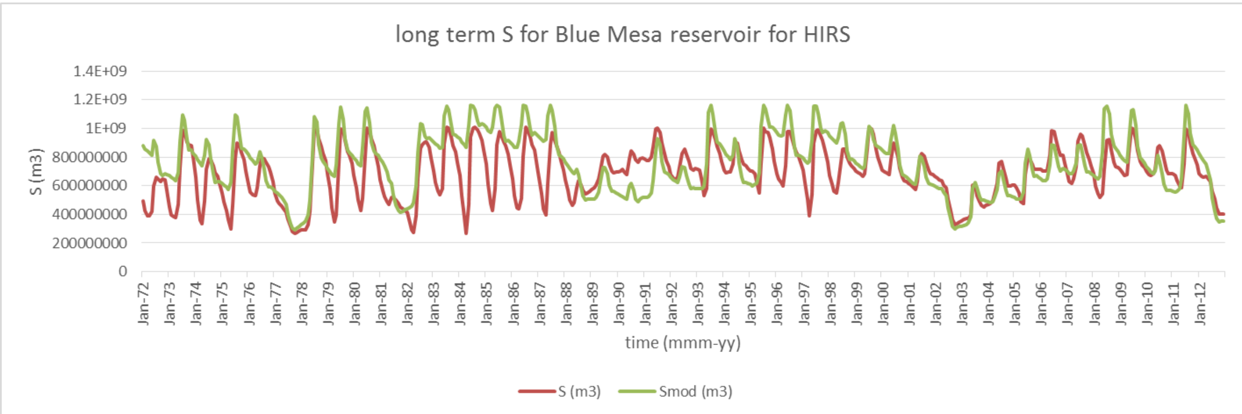

Qout for Blue Mesa reservoir for HIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

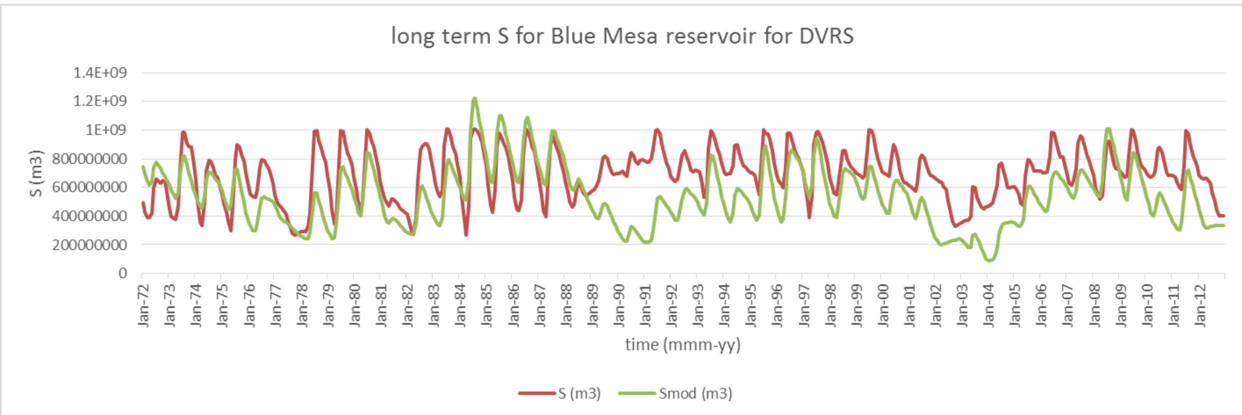

S for Blue Mesa reservoir for HIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)


Qout for Blue Mesa reservoir for DVRS
Q (m3/s)
200
180
160
140
120
100
80
60
40
20
0
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

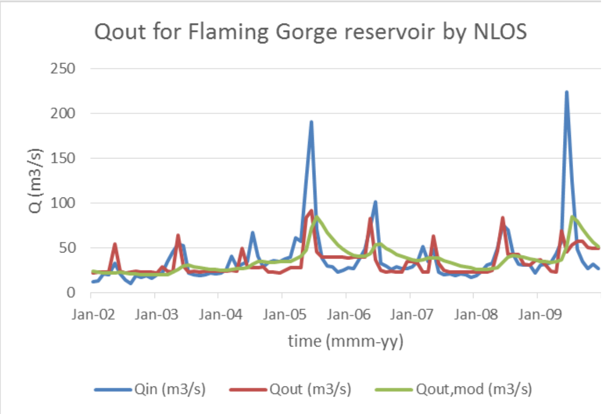

S for Blue Mesa reservoir for DVRS
S (m3)
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

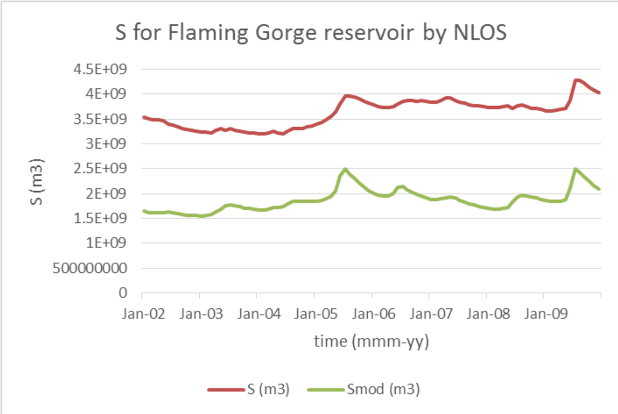

long term S for Blue Mesa reservoir for HNIRS
S (m3)
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
time (mmm-yy)
S (m3)
Smod (m3)

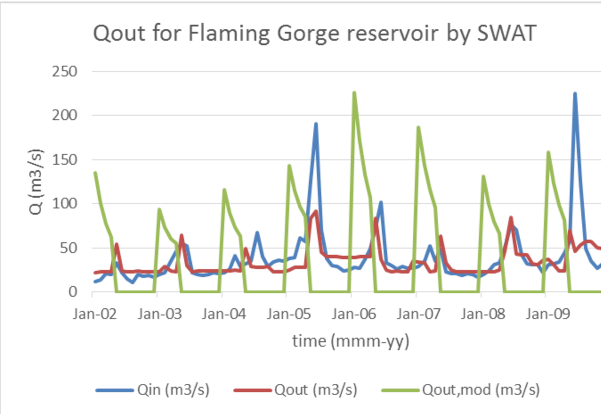

long term S for Blue Mesa reservoir for HIRS
S (m3)
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
time (mmm-yy)
S (m3)
Smod (m3)

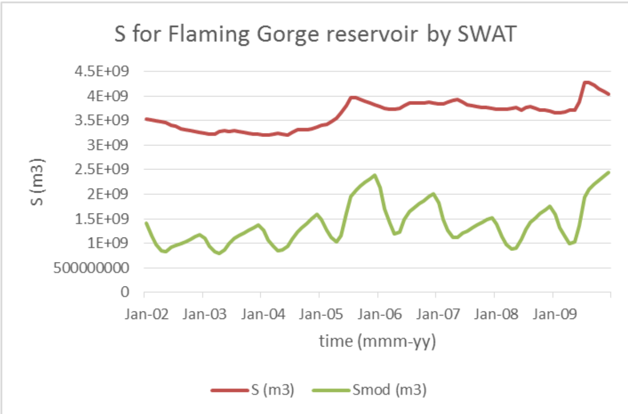

long term S for Blue Mesa reservoir for DVRS
S (m3)
1.4E+09
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
time (mmm-yy)
S (m3)
Smod (m3)

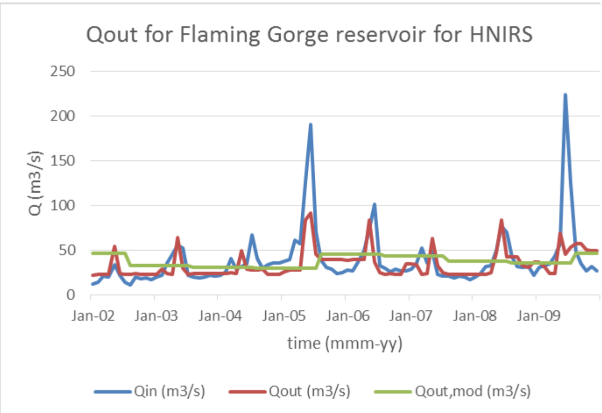
Flaming Gorge

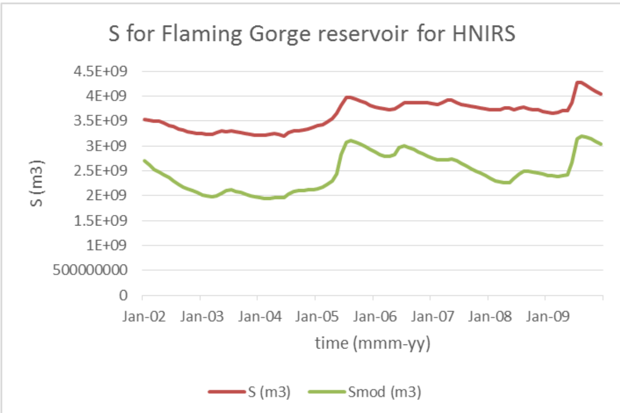


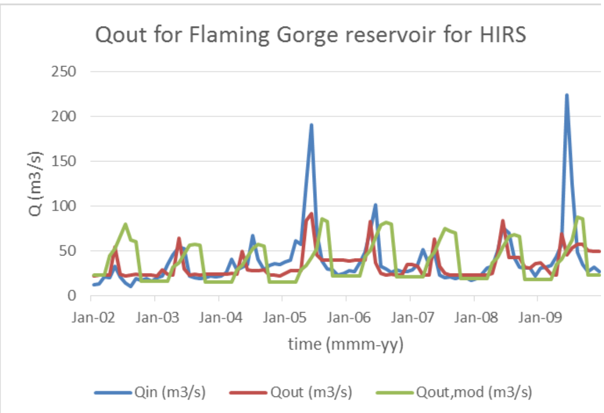


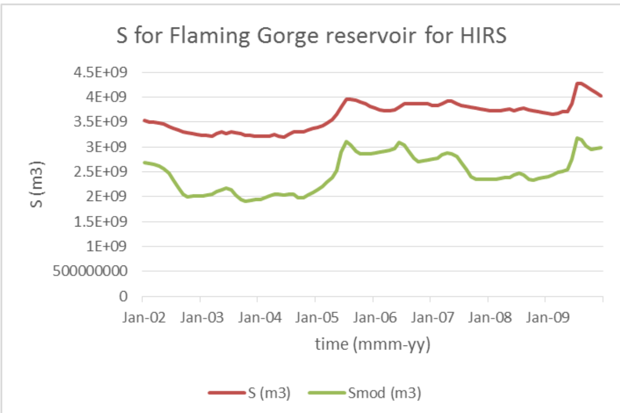


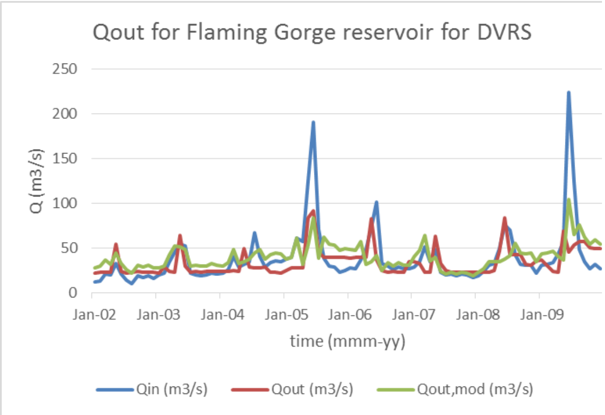


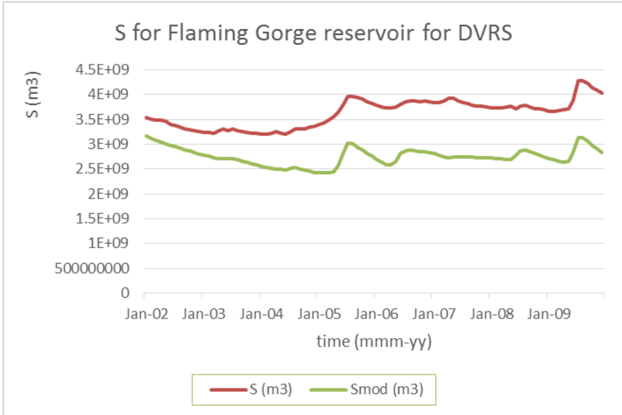


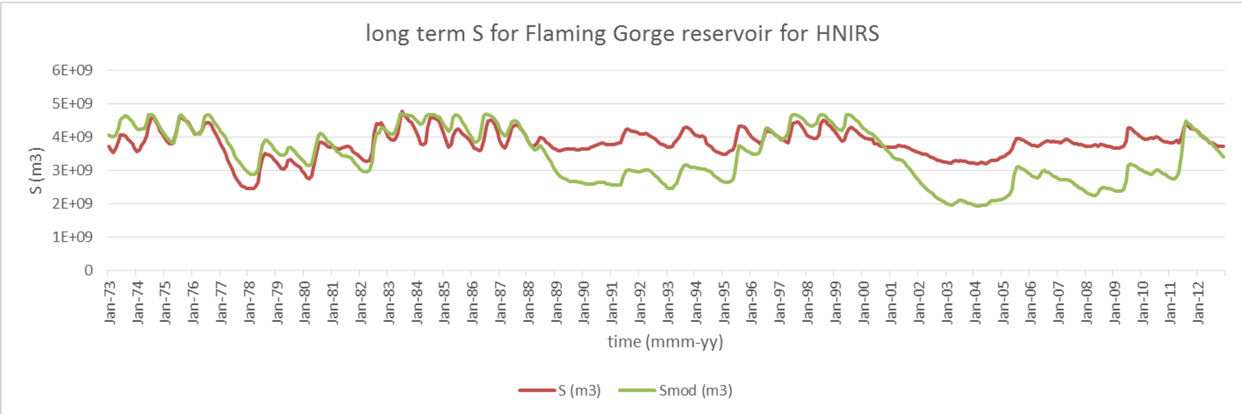


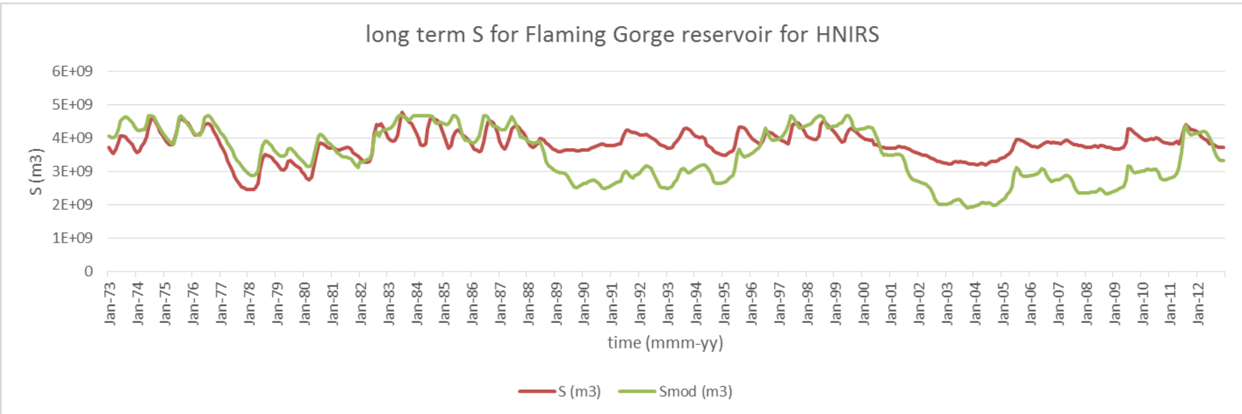


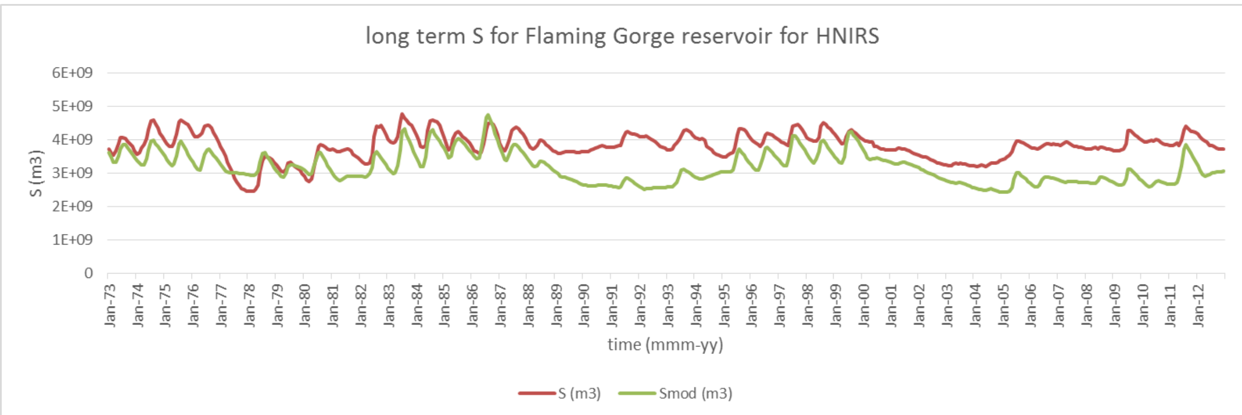



Qout for Flaming Gorge reservoir for DVRS
Q (m3/s)
250
200
150
100
50
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

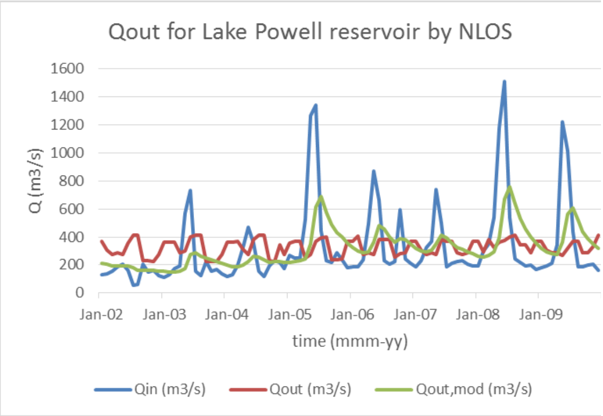

S for Flaming Gorge reservoir for DVRS
S (m3)
4.5E+09
4E+09
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

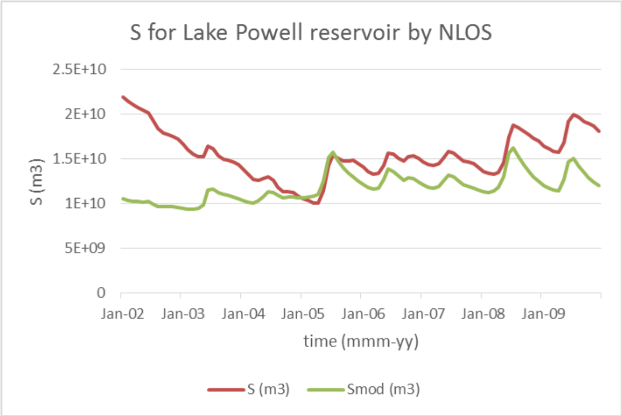

long term S for Flaming Gorge reservoir for HNIRS
S (m3)
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09 Jan-10 Jan-11 Jan-12
time (mmm-yy)
S (m3)
Smod (m3)

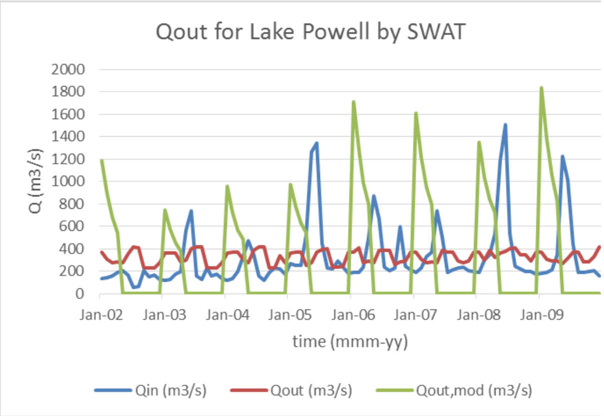

long term S for Flaming Gorge reservoir for HNIRS
S (m3)
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09 Jan-10 Jan-11 Jan-12
time (mmm-yy)
S (m3)
Smod (m3)

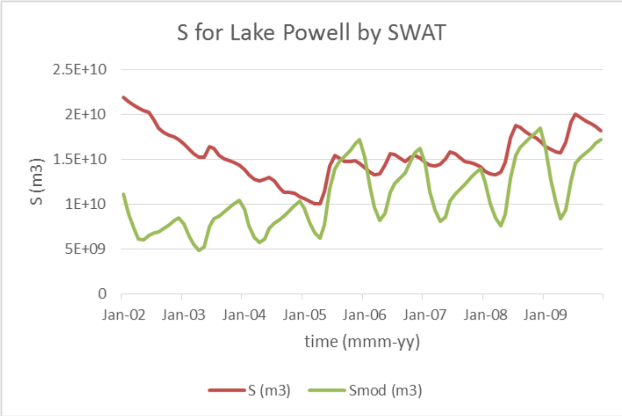

long term S for Flaming Gorge reservoir for HNIRS
S (m3)
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
Jan-73 Jan-74 Jan-75 Jan-76 Jan-77 Jan-78 Jan-79 Jan-80 Jan-81 Jan-82 Jan-83 Jan-84 Jan-85 Jan-86 Jan-87 Jan-88 Jan-89 Jan-90 Jan-91 Jan-92 Jan-93 Jan-94 Jan-95 Jan-96 Jan-97 Jan-98 Jan-99 Jan-00 Jan-01 Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09 Jan-10 Jan-11 Jan-12
time (mmm-yy)
S (m3)
Smod (m3)

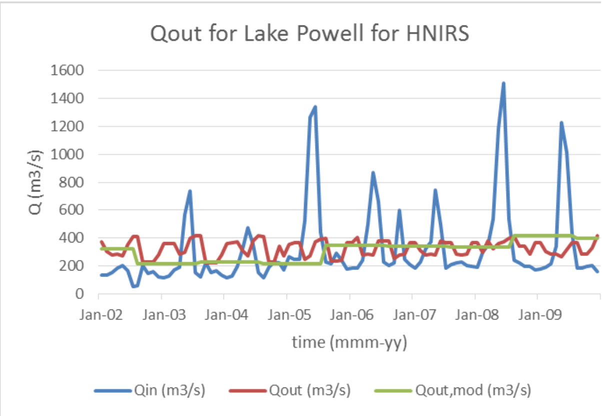
Lake Powell

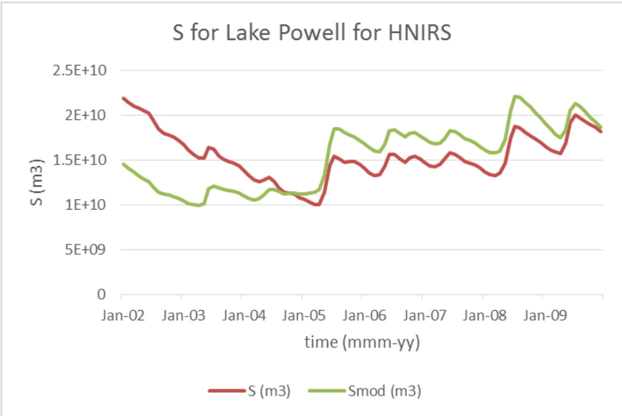

Qout for Lake Powell reservoir by NLOS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

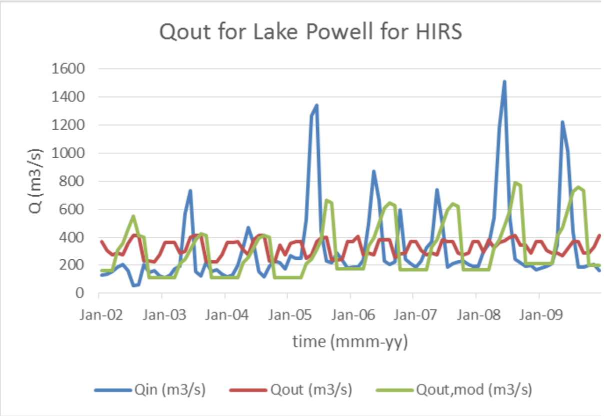

S for Lake Powell reservoir by NLOS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

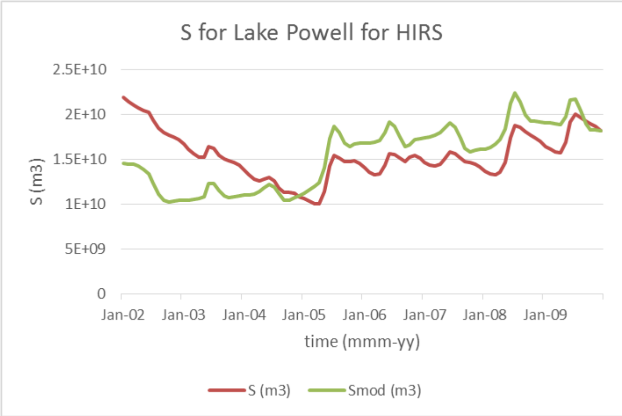

Qout for Lake Powell by SWAT
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

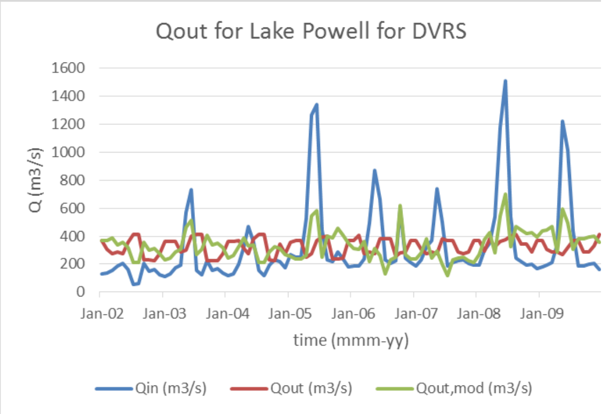

S for Lake Powell by SWAT
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

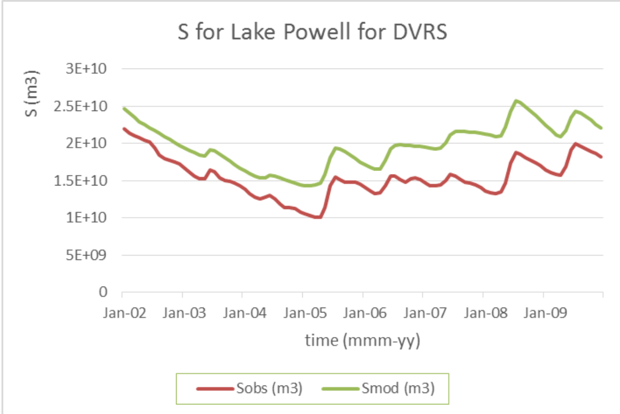

Qout for Lake Powell for HNIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

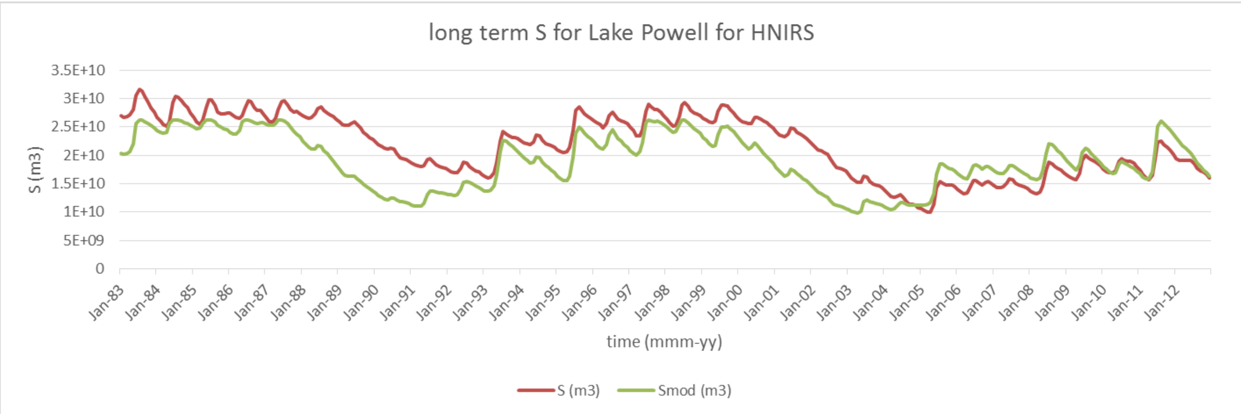

S for Lake Powell for HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

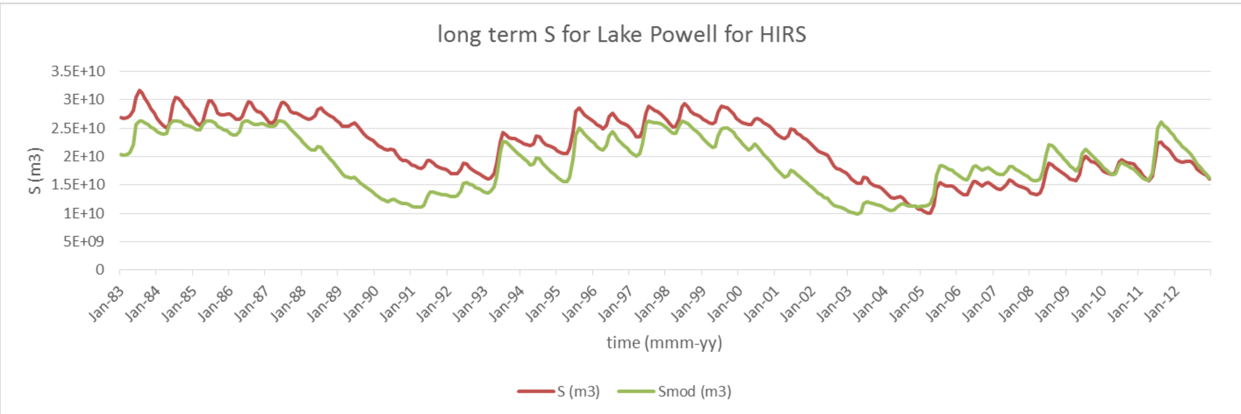

Qout for Lake Powell for HIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)

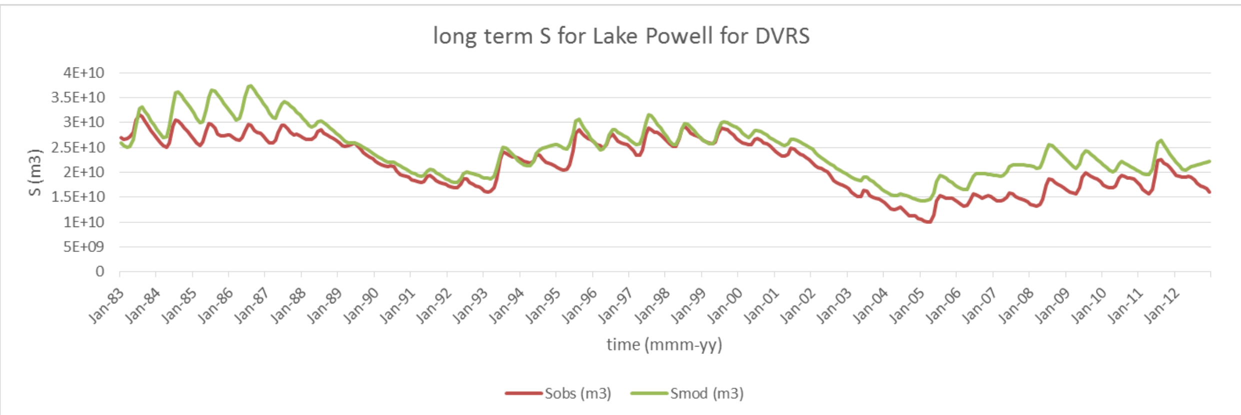

S for Lake Powell for HIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)


Qout for Lake Powell for DVRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout (m3/s)
Qout,mod (m3/s)


S for Lake Powell for DVRS
S (m3)
time (mmm-yy)
Sobs (m3)
Smod (m3)


long term S for Lake Powell for HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

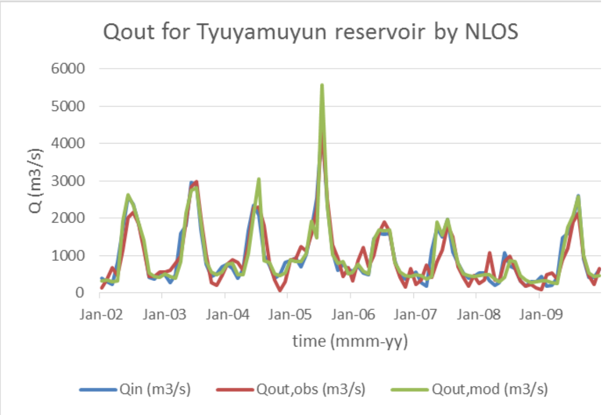

long term S for Lake Powell for HIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)


long term S for Lake Powell for DVRS
S (m3)
time (mmm-yy)
Sobs (m3)
Smod (m3)

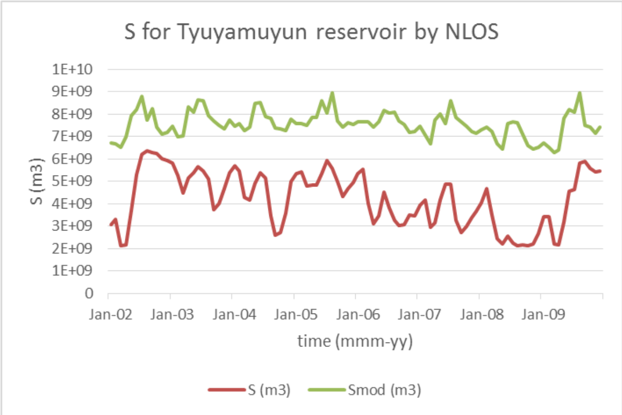
Appendix B

Reservoirs in Central Asia

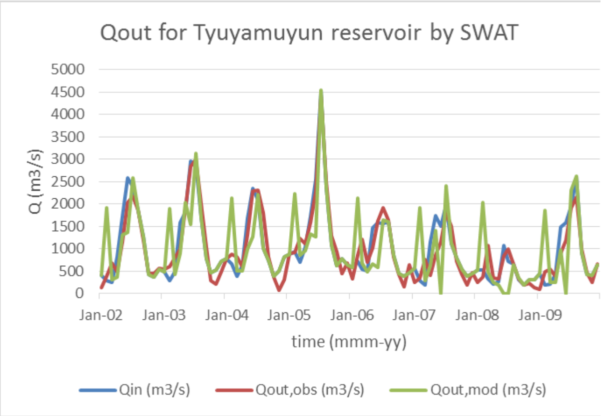
Tyuyamuyun



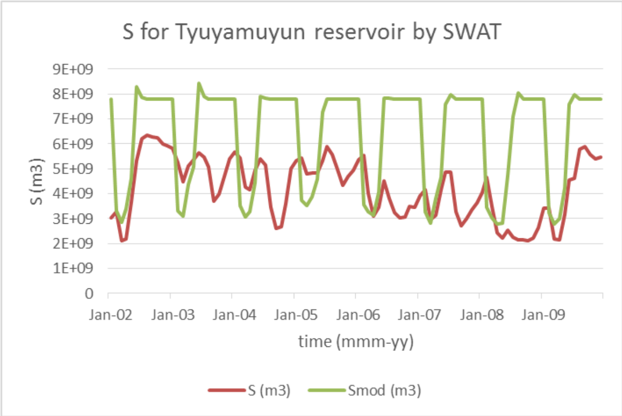
Qout for Tyuyamuyun reservoir by NLOS
6000
5000
4000
3000
2000
1000
0
Q (m3/s)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



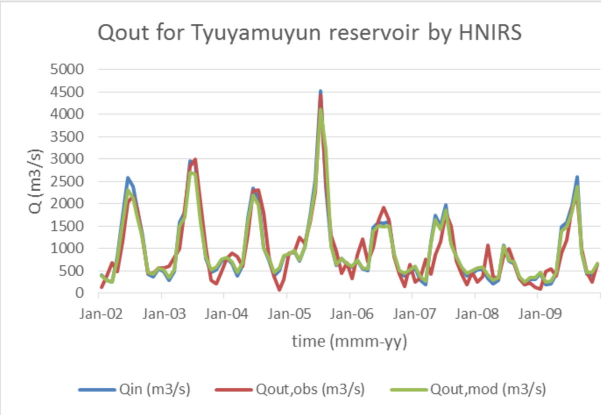
S for Tyuyamuyun reservoir by NLOS
1E+10
9E+09
8E+09
7E+09
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
S (m3)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)



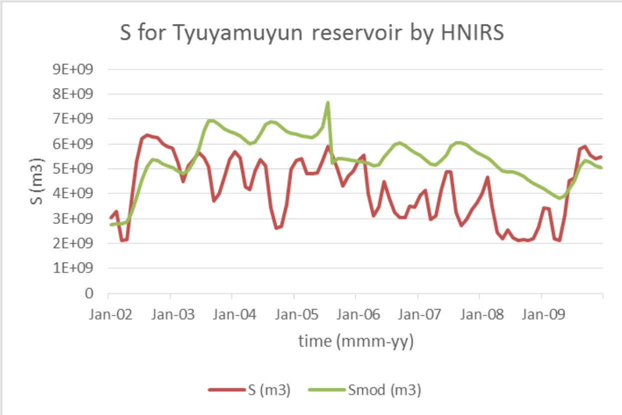
Qout for Tyuyamuyun reservoir by SWAT
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Q (m3/s)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



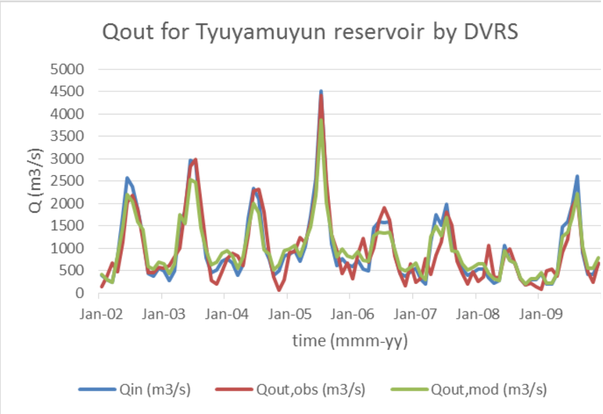
S for Tyuyamuyun reservoir by SWAT
9E+09
8E+09
7E+09
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
S (m3)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)



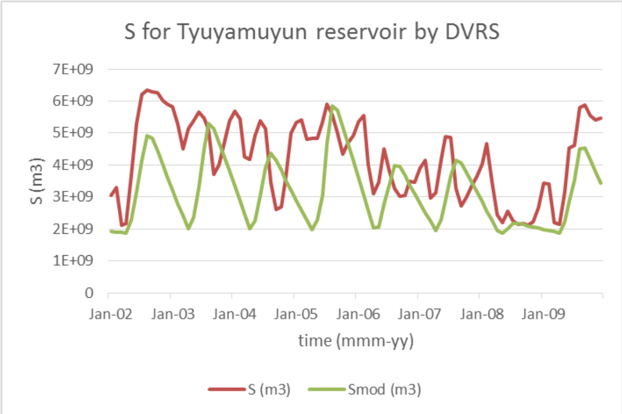
Qout for Tyuyamuyun reservoir by HNIRS
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Q (m3/s)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



S for Tyuyamuyun reservoir by HNIRS
9E+09
8E+09
7E+09
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
S (m3)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

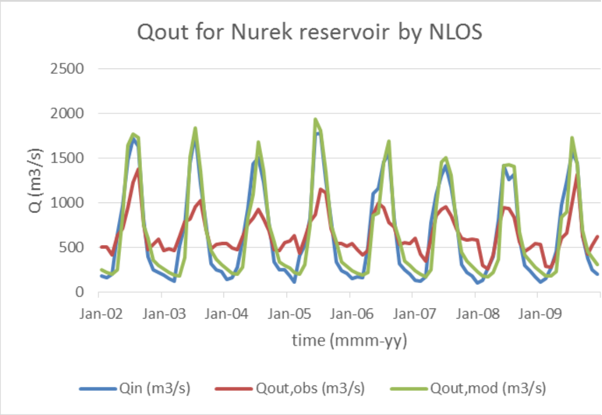


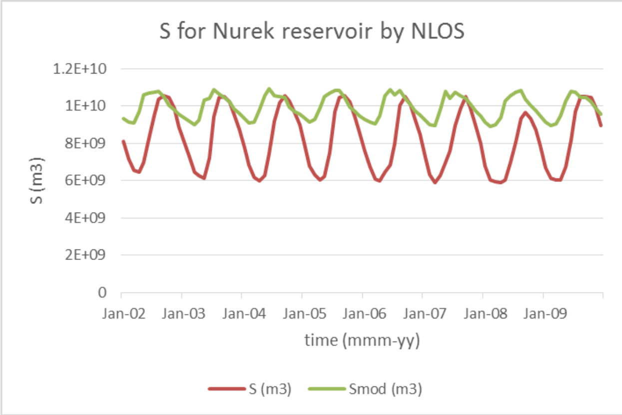
Qout for Tyuyamuyun reservoir by DVRS
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Q (m3/s)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

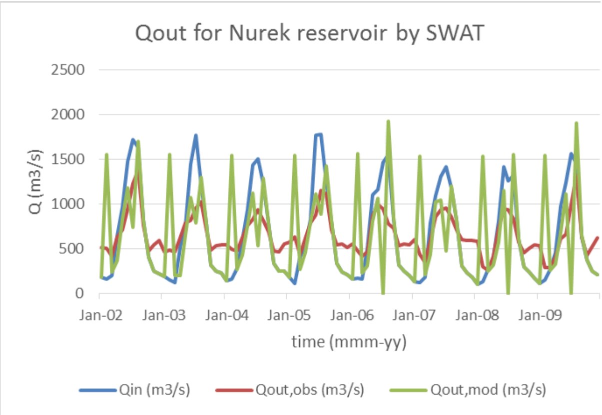


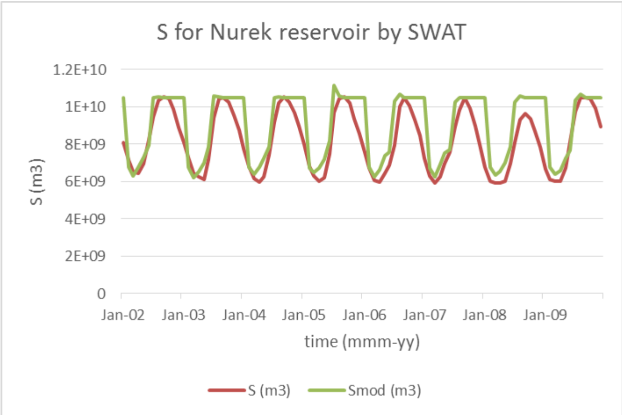
S for Tyuyamuyun reservoir by DVRS
7E+09
6E+09
5E+09
4E+09
3E+09
2E+09
1E+09
0
S (m3)
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

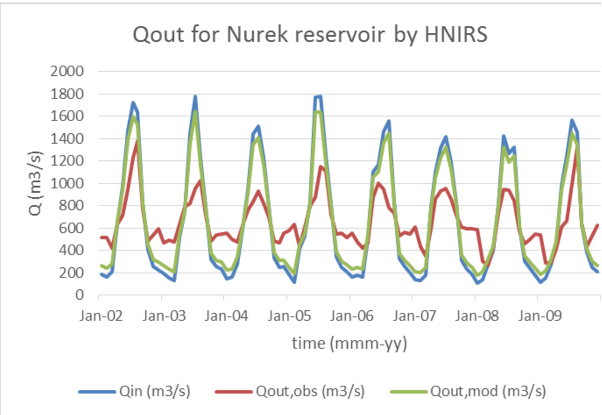
Nurek

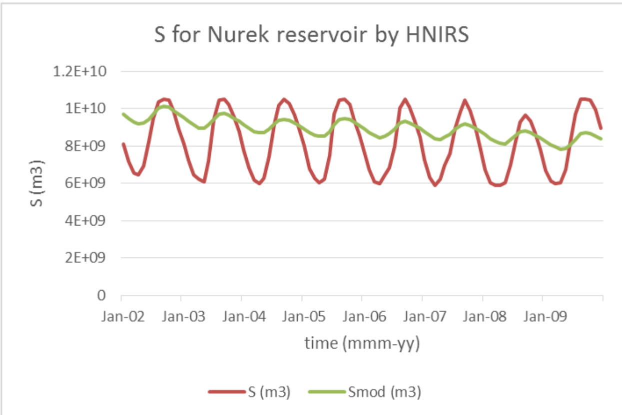

Qout for Nurek reservoir by NLOS
2500
2000
1500
1000
500
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

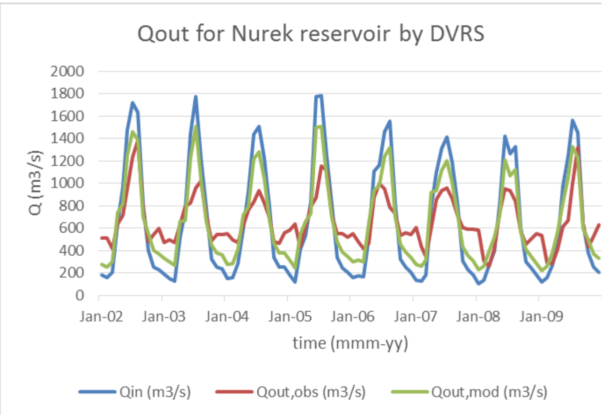

S for Nurek reservoir by NLOS
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

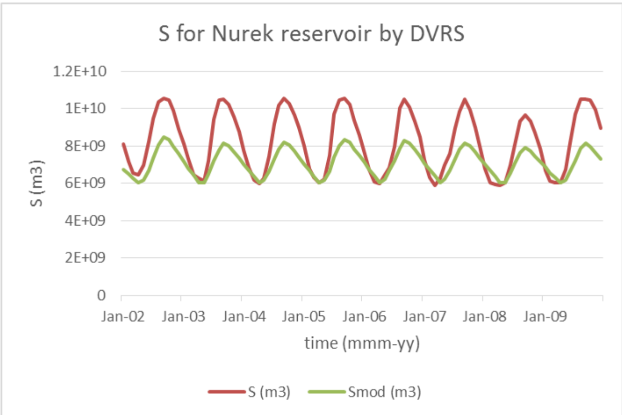

Qout for Nurek reservoir by SWAT
2500
2000
1500
1000
500
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Nurek reservoir by SWAT
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

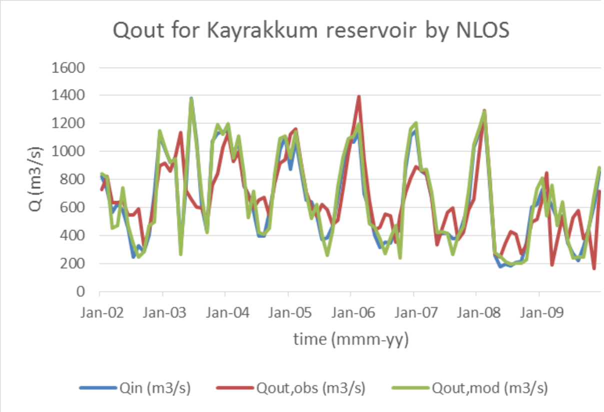

Qout for Nurek reservoir by HNIRS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

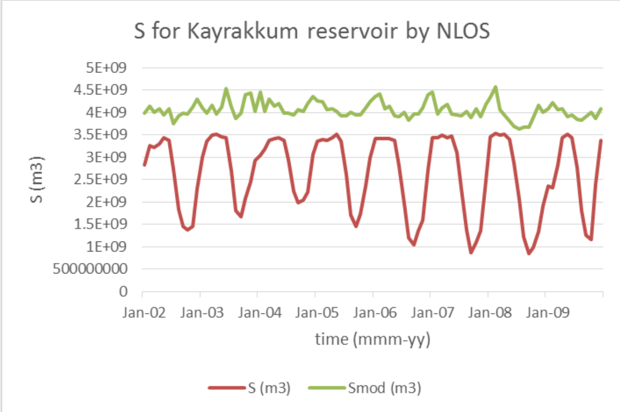

S for Nurek reservoir by HNIRS
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

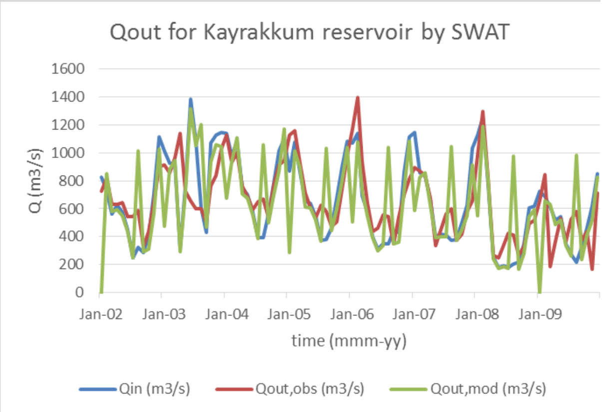

Qout for Nurek reservoir by DVRS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

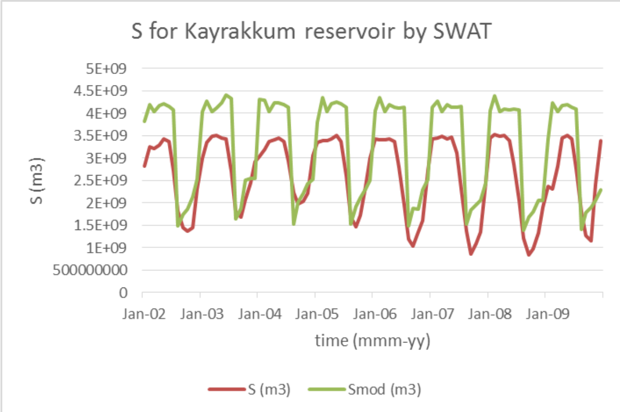

S for Nurek reservoir by DVRS
1.2E+10
1E+10
8E+09
6E+09
4E+09
2E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

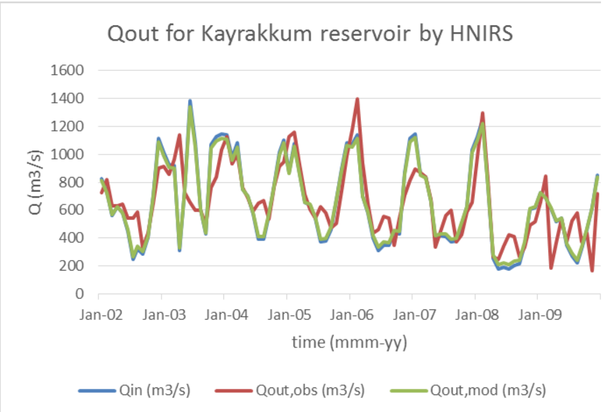
Kayrakkum

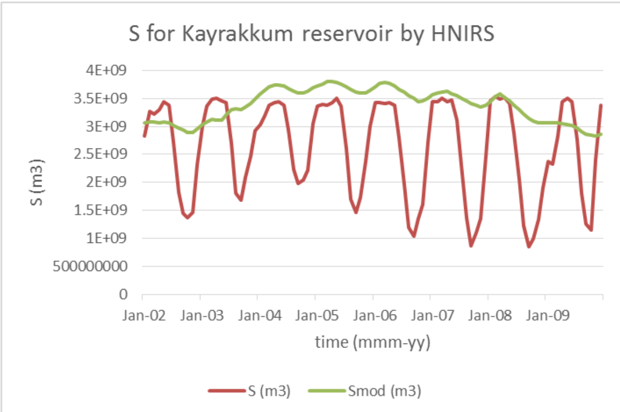

Qout for Kayrakkum reservoir by NLOS
Q (m3/s)
1600
1400
1200
1000
800
600
400
200
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

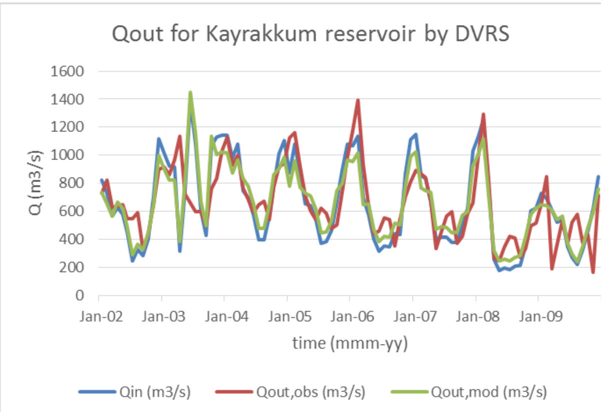

S for Kayrakkum reservoir by NLOS
S (m3)
5E+09
4.5E+09
4E+09
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

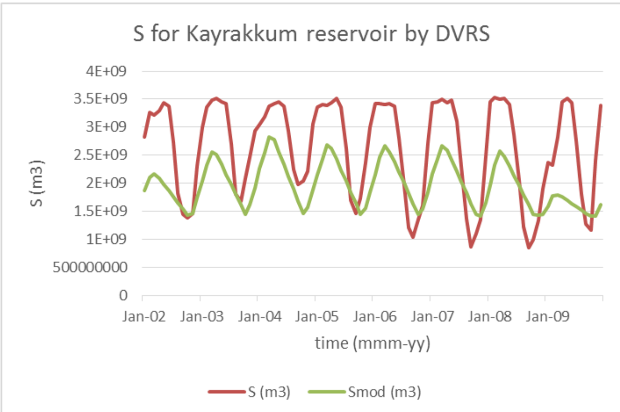

Qout for Kayrakkum reservoir by SWAT
Q (m3/s)
1600
1400
1200
1000
800
600
400
200
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Kayrakkum reservoir by SWAT
S (m3)
5E+09
4.5E+09
4E+09
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

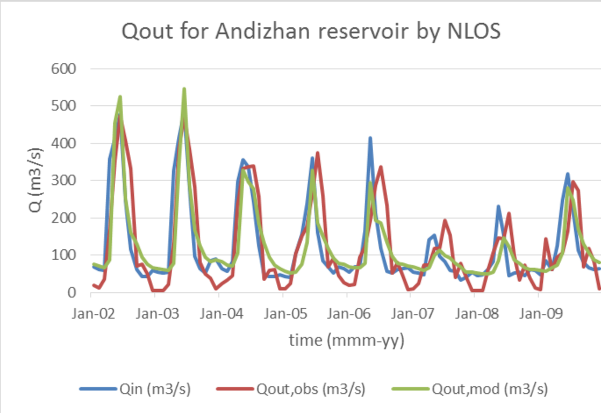

Qout for Kayrakkum reservoir by HNIRS
Q (m3/s)
1600
1400
1200
1000
800
600
400
200
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Kayrakkum reservoir by HNIRS
S (m3)
4E+09
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

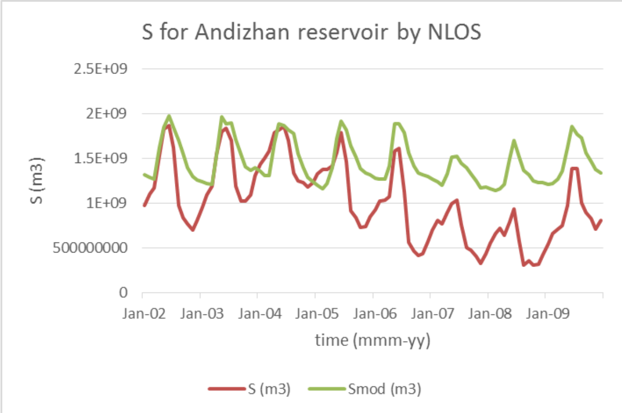

Qout for Kayrakkum reservoir by DVRS
Q (m3/s)
1600
1400
1200
1000
800
600
400
200
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Kayrakkum reservoir by DVRS
S (m3)
4E+09
3.5E+09
3E+09
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

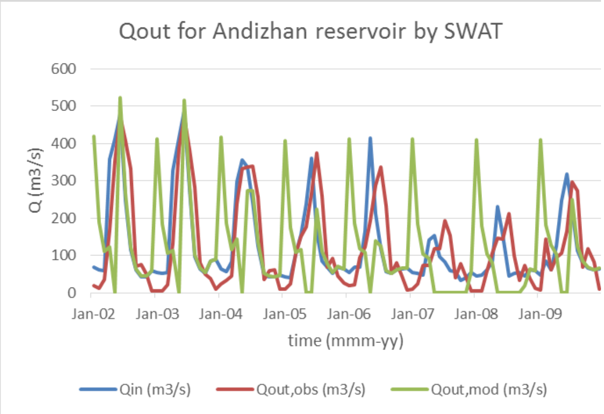
Andizhan



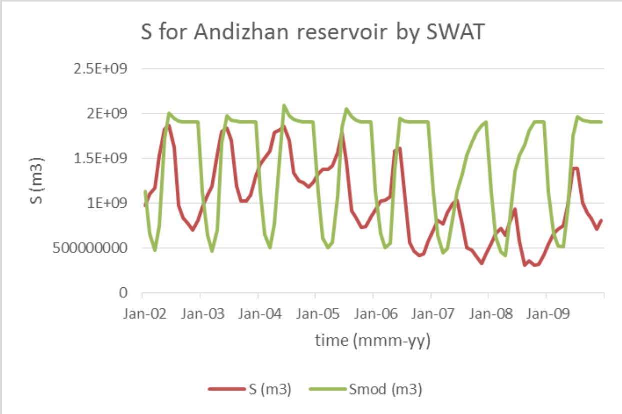
Qout for Andizhan reservoir by NLOS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



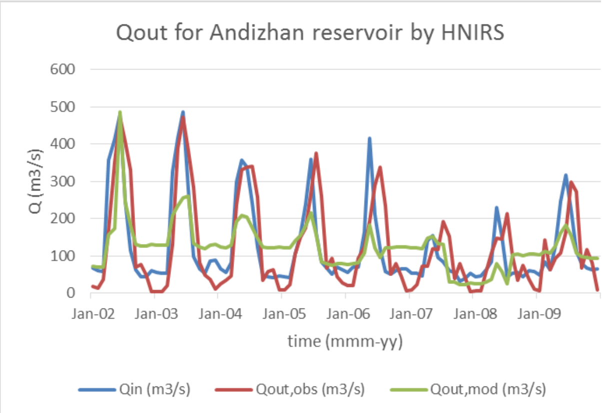
S for Andizhan reservoir by NLOS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)



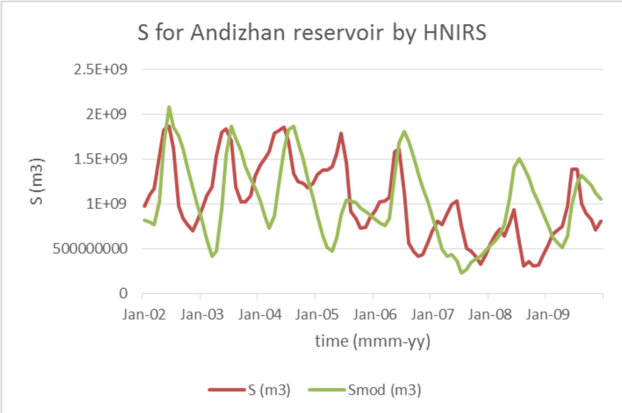
Qout for Andizhan reservoir by SWAT
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



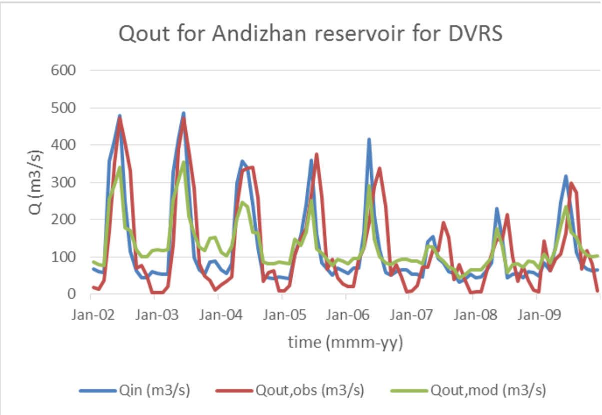
S for Andizhan reservoir by SWAT
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)



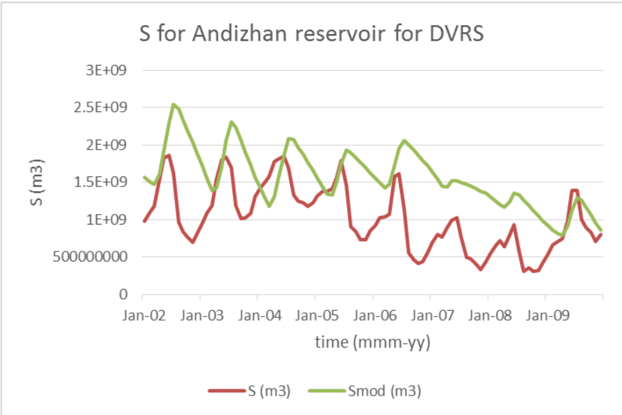
Qout for Andizhan reservoir by HNIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)



S for Andizhan reservoir by HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

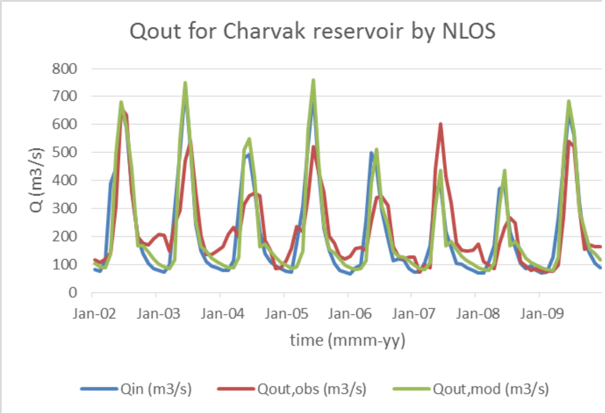


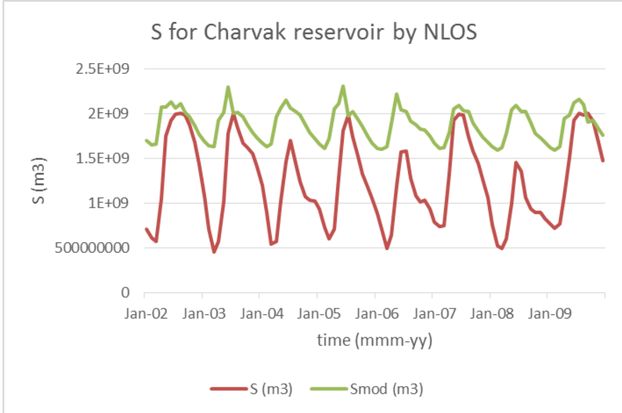
Qout for Andizhan reservoir for DVRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

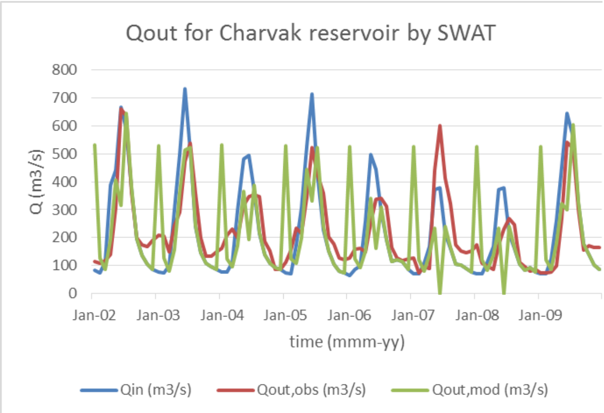


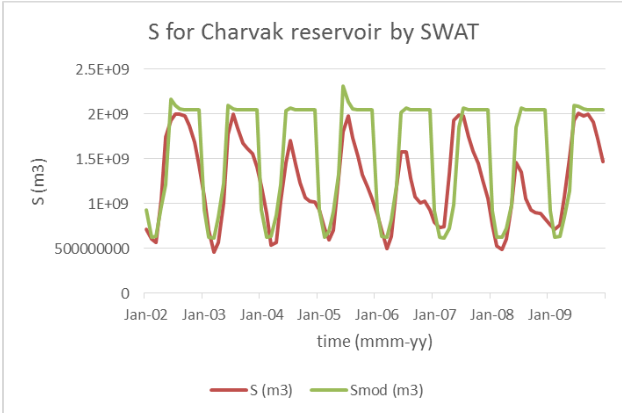
S for Andizhan reservoir for DVRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

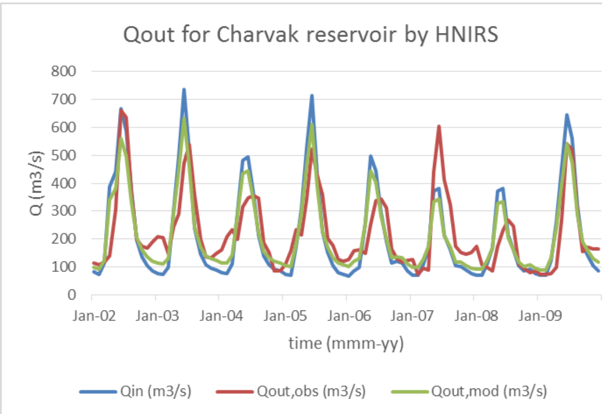
Charvak

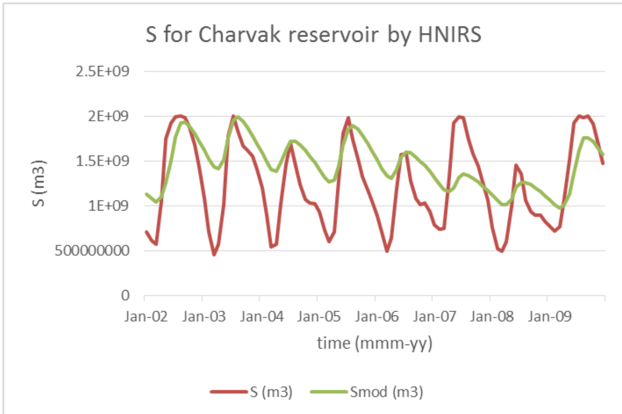

Qout for Charvak reservoir by NLOS
Q (m3/s)
0
100
200
300
400
500
600
700
800
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

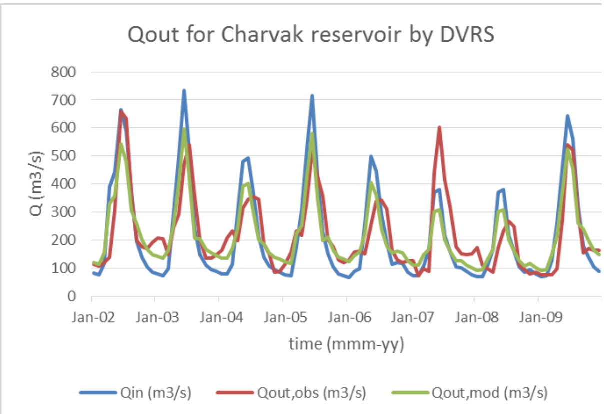

S for Charvak reservoir by NLOS
S (m3)
0
500000000
1E+09
1.5E+09
2E+09
2.5E+09
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

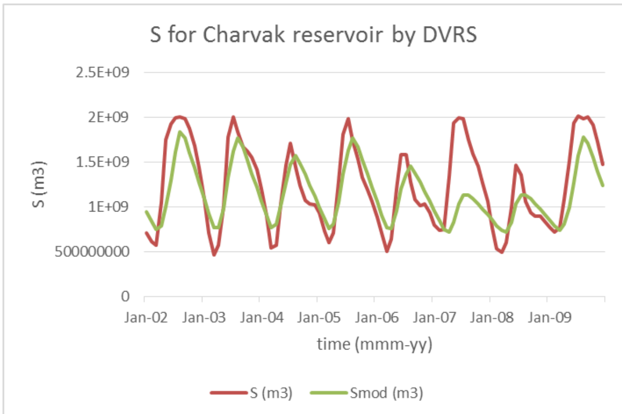

Qout for Charvak reservoir by SWAT
Q (m3/s)
0
100
200
300
400
500
600
700
800
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Charvak reservoir by SWAT
S (m3)
0
500000000
1E+09
1.5E+09
2E+09
2.5E+09
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

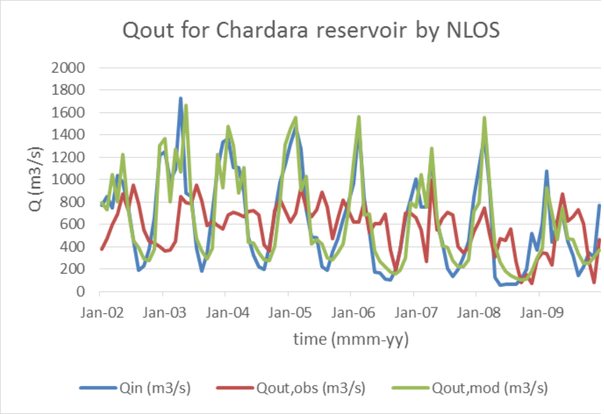

Qout for Charvak reservoir by HNIRS
Q (m3/s)
0
100
200
300
400
500
600
700
800
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

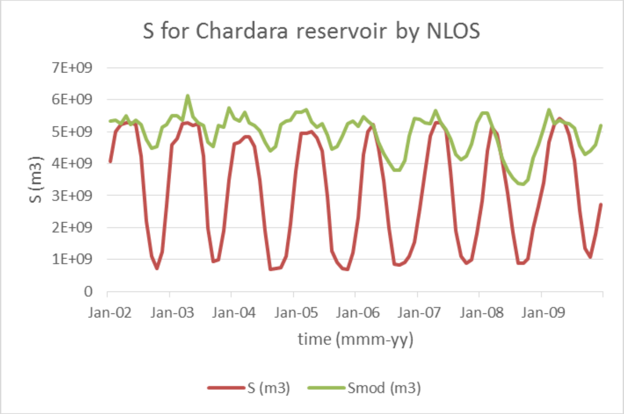

S for Charvak reservoir by HNIRS
S (m3)
0
500000000
1E+09
1.5E+09
2E+09
2.5E+09
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

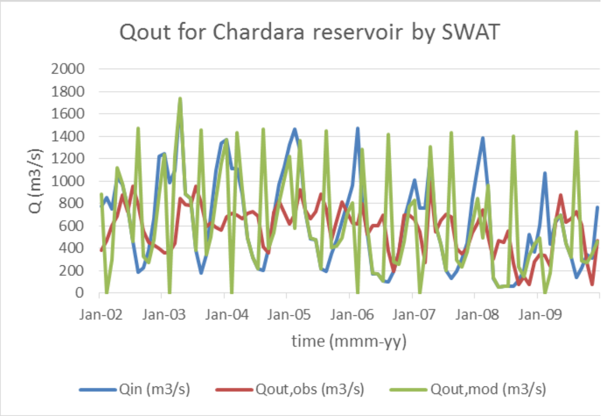

Qout for Charvak reservoir by DVRS
Q (m3/s)
0
100
200
300
400
500
600
700
800
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

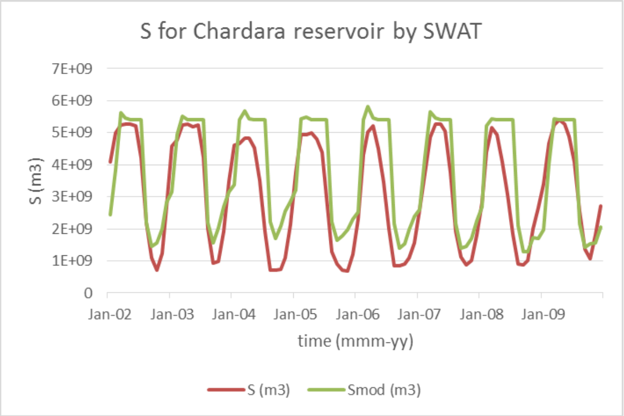

S for Charvak reservoir by DVRS
S (m3)
0
500000000
1E+09
1.5E+09
2E+09
2.5E+09
Jan-02
Jan-03
Jan-04
Jan-05
Jan-06
Jan-07
Jan-08
Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

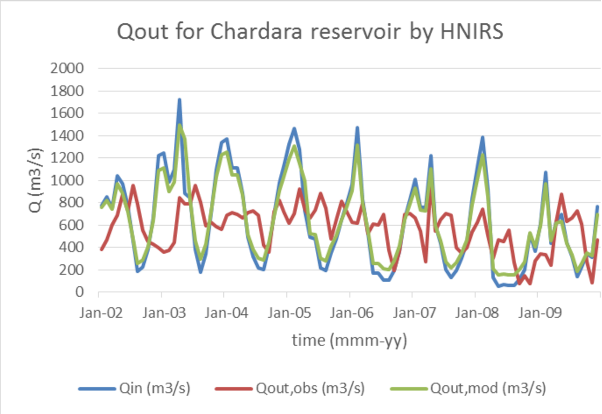
Chardara

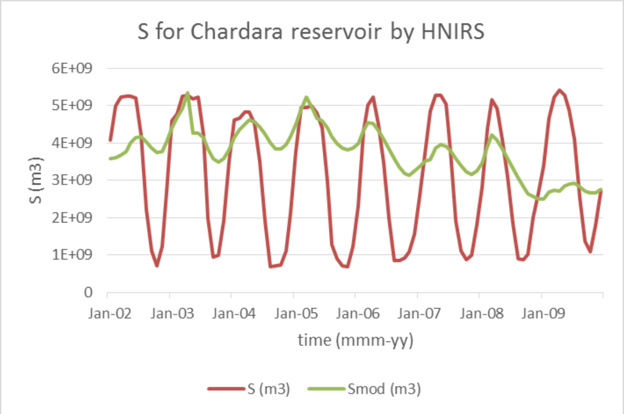

Qout for Chardara reservoir by NLOS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

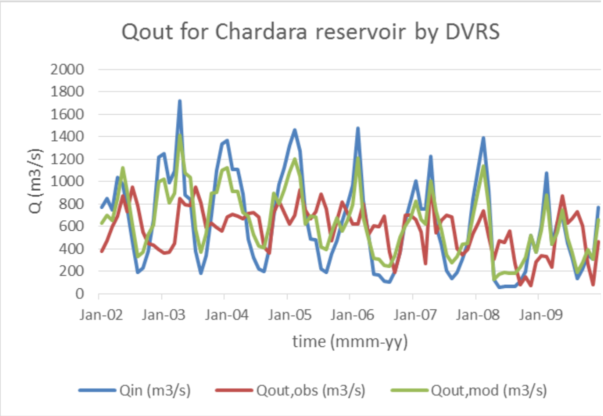

S for Chardara reservoir by NLOS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

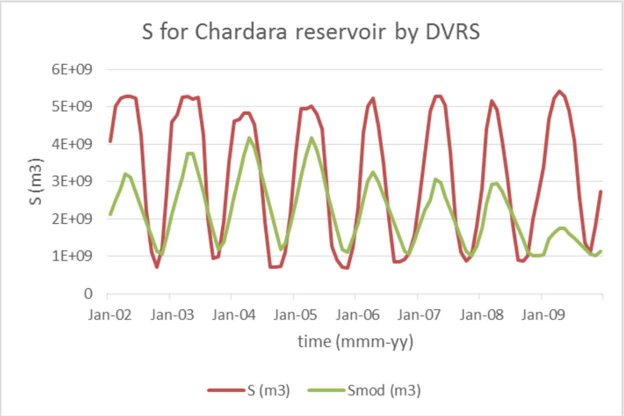

Qout for Chardara reservoir by SWAT
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Chardara reservoir by SWAT
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

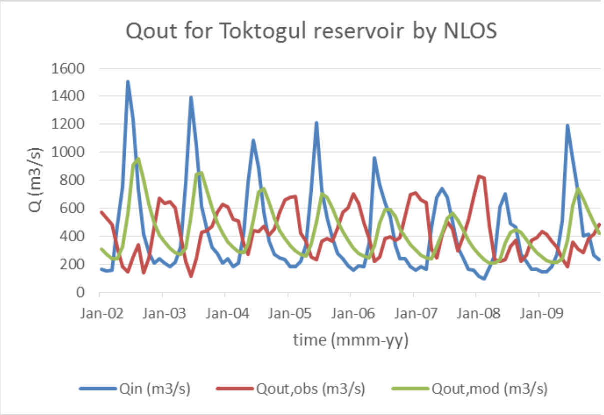

Qout for Chardara reservoir by HNIRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

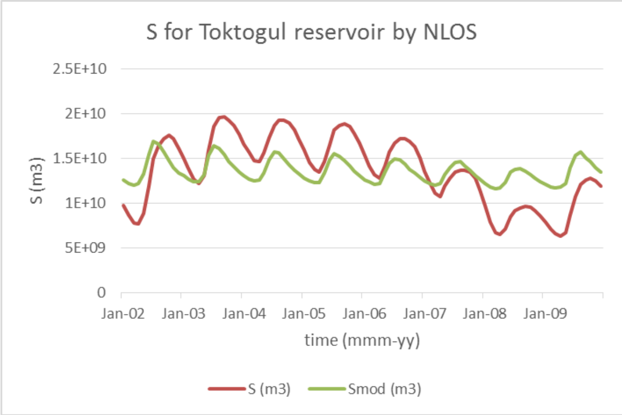

S for Chardara reservoir by HNIRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

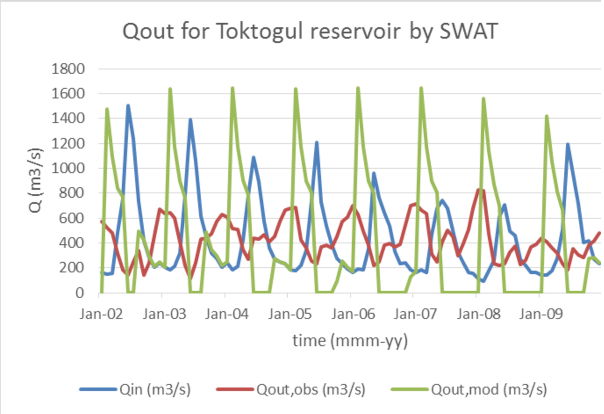

Qout for Chardara reservoir by DVRS
Q (m3/s)
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

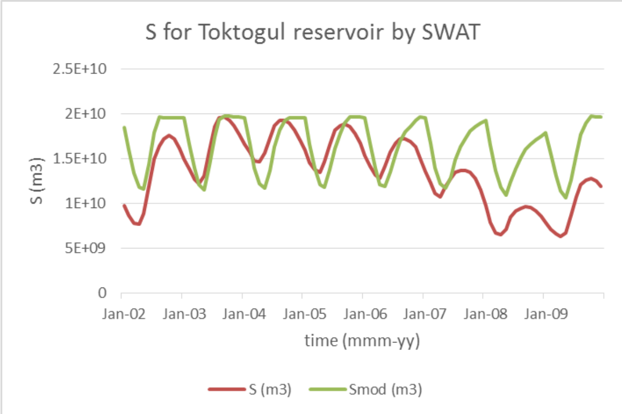

S for Chardara reservoir by DVRS
S (m3)
time (mmm-yy)
S (m3)
Smod (m3)

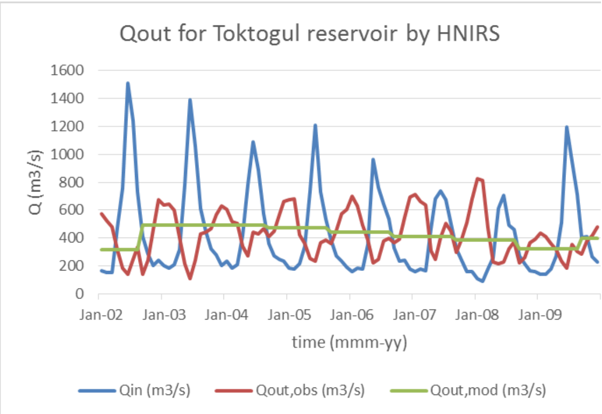
Toktogul

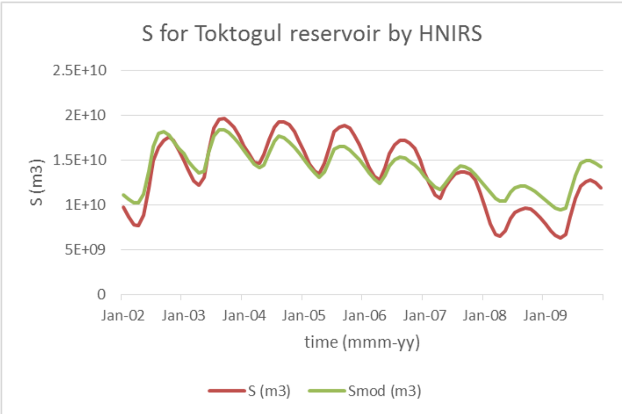

Qout for Toktogul reservoir by NLOS
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

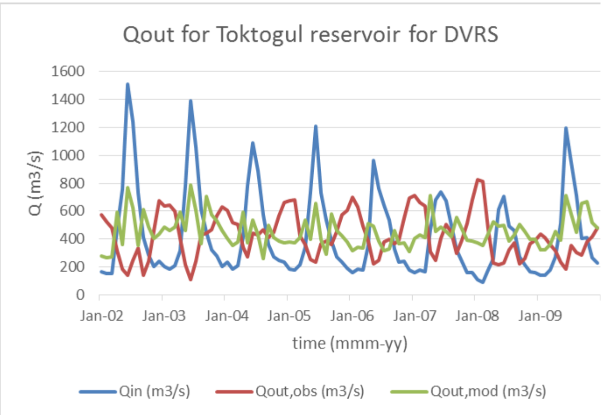

S for Toktogul reservoir by NLOS
2.5E+10
2E+10
1.5E+10
1E+10
5E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

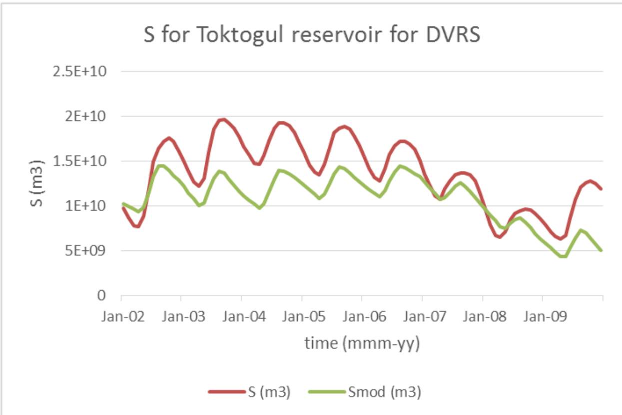

Qout for Toktogul reservoir by SWAT
1800
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Toktogul reservoir by SWAT
2.5E+10
2E+10
1.5E+10
1E+10
5E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)


Qout for Toktogul reservoir by HNIRS
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Toktogul reservoir by HNIRS
2.5E+10
2E+10
1.5E+10
1E+10
5E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

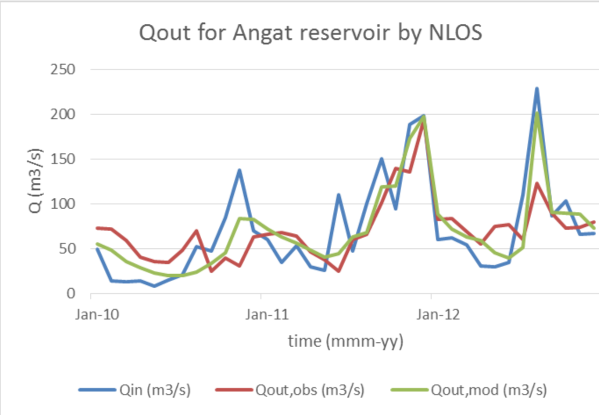

Qout for Toktogul reservoir for DVRS
1600
1400
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

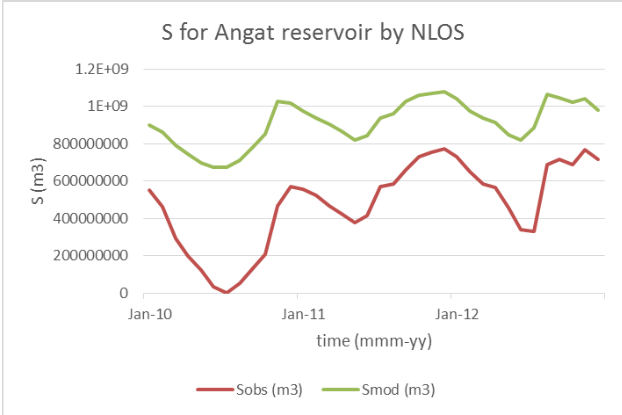

S for Toktogul reservoir for DVRS
2.5E+10
2E+10
1.5E+10
1E+10
5E+09
0
S (m3)
Jan-02 Jan-03 Jan-04 Jan-05 Jan-06 Jan-07 Jan-08 Jan-09
time (mmm-yy)
S (m3)
Smod (m3)

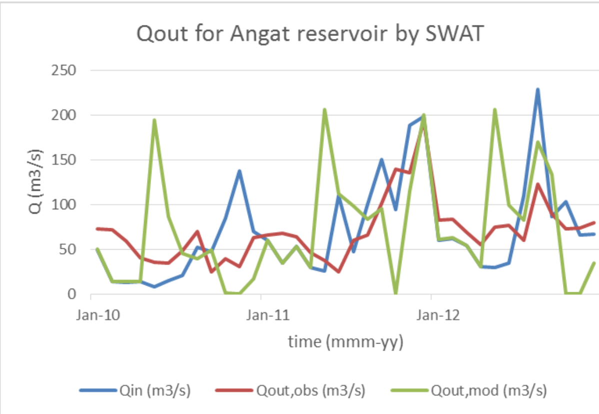
Appendix C

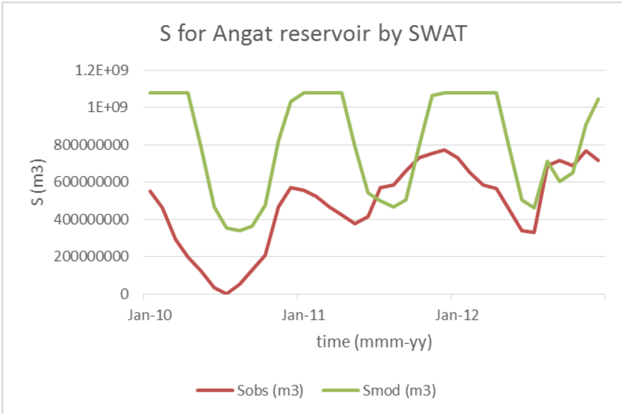
Reservoirs in Southeast Asia

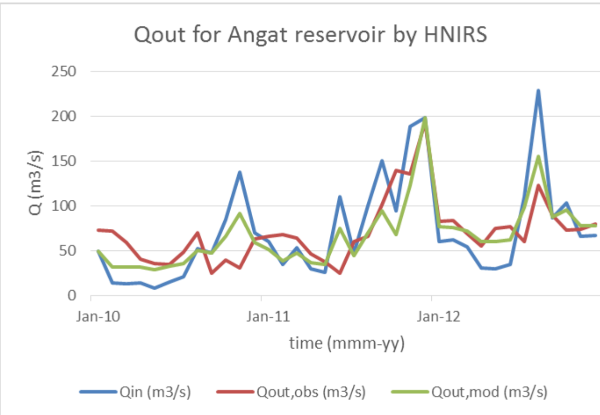
Angat

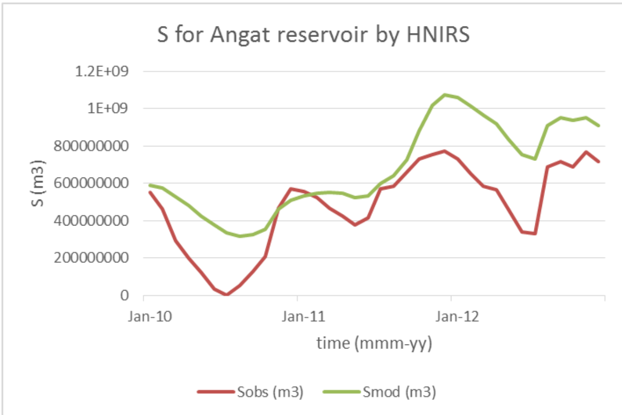

Qout for Angat reservoir by NLOS
250
200
150
100
50
0
Q (m3/s)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

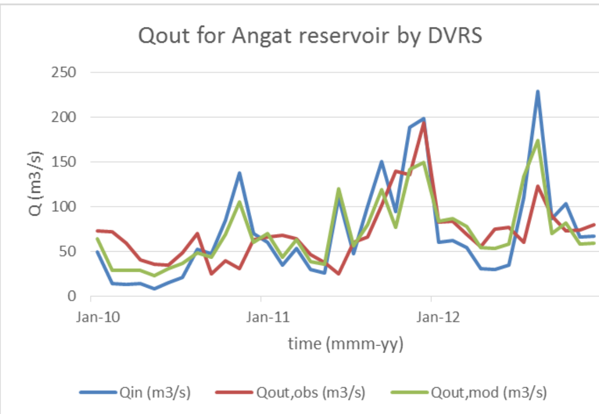

S for Angat reservoir by NLOS
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Sobs (m3)
Smod (m3)

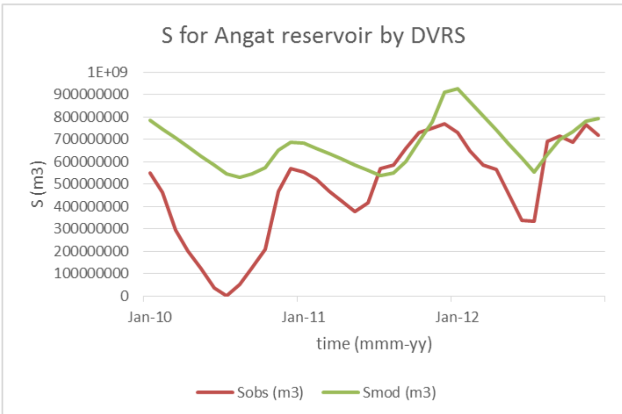

Qout for Angat reservoir by SWAT
250
200
150
100
50
0
Q (m3/s)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Angat reservoir by SWAT
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Sobs (m3)
Smod (m3)

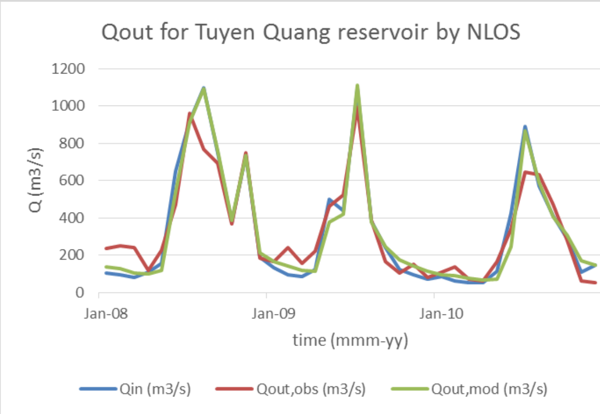

Qout for Angat reservoir by HNIRS
250
200
150
100
50
0
Q (m3/s)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

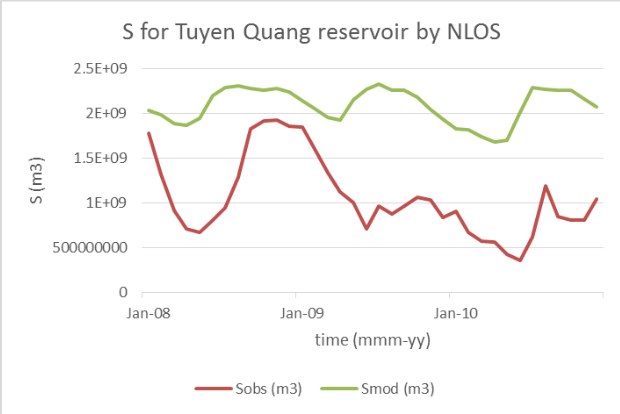

S for Angat reservoir by HNIRS
1.2E+09
1E+09
800000000
600000000
400000000
200000000
0
S (m3)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Sobs (m3)
Smod (m3)

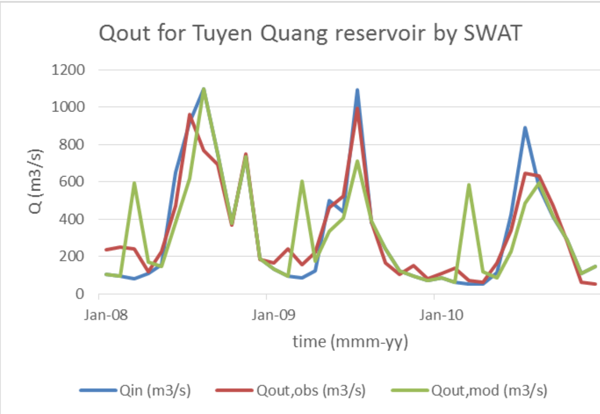

Qout for Angat reservoir by DVRS
250
200
150
100
50
0
Q (m3/s)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

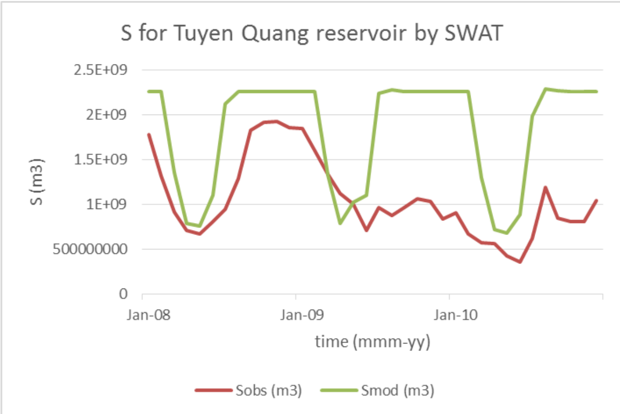

S for Angat reservoir by DVRS
1E+09
900000000
800000000
700000000
600000000
500000000
400000000
300000000
200000000
100000000
0
S (m3)
Jan-10
Jan-11
Jan-12
time (mmm-yy)
Sobs (m3)
Smod (m3)

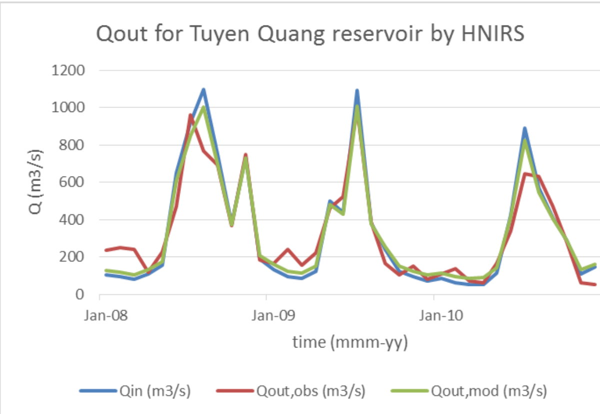
Tuyen Quang

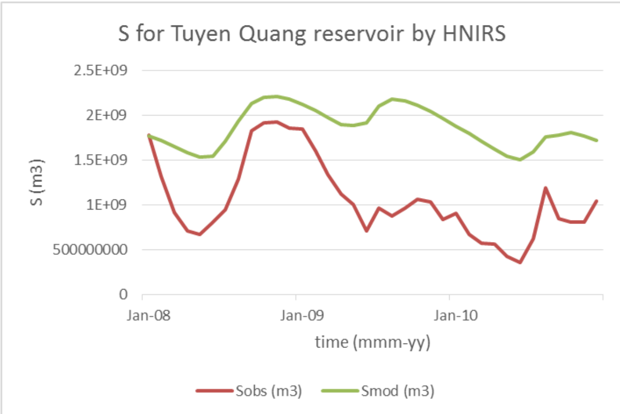

Qout for Tuyen Quang reservoir by NLOS
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)

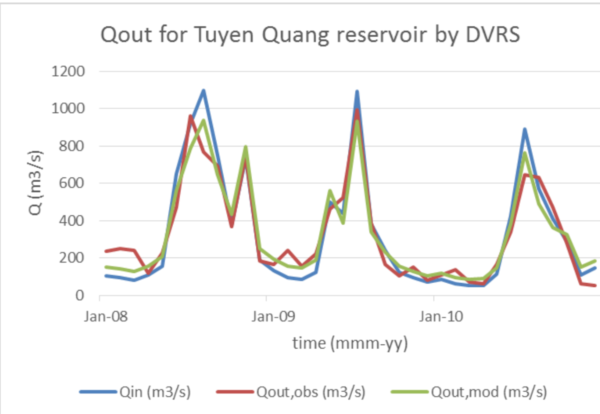

S for Tuyen Quang reservoir by NLOS
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
S (m3)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Sobs (m3)
Smod (m3)

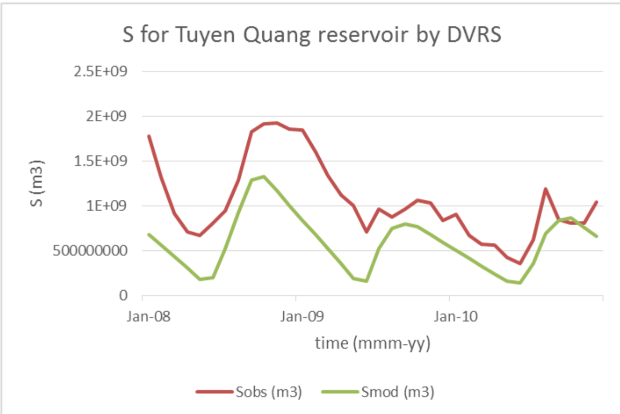

Qout for Tuyen Quang reservoir by SWAT
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Tuyen Quang reservoir by SWAT
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
S (m3)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Sobs (m3)
Smod (m3)


Qout for Tuyen Quang reservoir by HNIRS
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Tuyen Quang reservoir by HNIRS
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
S (m3)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Sobs (m3)
Smod (m3)


Qout for Tuyen Quang reservoir by DVRS
1200
1000
800
600
400
200
0
Q (m3/s)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Qin (m3/s)
Qout,obs (m3/s)
Qout,mod (m3/s)


S for Tuyen Quang reservoir by DVRS
2.5E+09
2E+09
1.5E+09
1E+09
500000000
0
S (m3)
Jan-08
Jan-09
Jan-10
time (mmm-yy)
Sobs (m3)
Smod (m3)