RECLAMATION
Managing Water in the West

Research Project - Generalized Stream Flow Depletions Model for Historic and Projected Future Climate Scenarios

Research and Development Office
Science and Technology Program
Final Report: ID Number 8013

Research and Development Office
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October 2014
Christopher O. Murray, P.E.

Mission Statements

The U.S. Department of the Interior protects America's natural resources and heritage, honors our cultures and tribal communities, and supplies the energy to power our future.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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For water managers, having good stream flow depletion data is critical to keeping accurate water balance equations to inform the allocation decision process. The Great Plains Region (GP) has dealt with this issue in the Missouri River Basin by developing a model, which calculates the stream depletions, by reach, using actual irrigated acres and crop water requirement calculations. GP has been improving this model for the past two decades, and currently has an adequate model of the Missouri River Basin. The following factors have resulted in a need for model upgrade:

- The equations in the model do not reflect the state of the art in crop water use calculations.
- Climate change has become a large part of the planning process.
- GP has realized this model could be generalized to work in other basins.
- Considerable interest in the model from outside agencies has been observed.

GP has scoped a project to update, upgrade, generalize, and distribute this model so that it can be used for processing historical depletions and global climate model (GCM) outputs to analyze the changes in stream flow depletions resulting from modeled climate scenarios and historical water use.

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Peer Reviewer: I have reviewed the assigned items/sections(s) noted for the above document and believe them to be in accordance with the project requirements, standards of the profession, and Reclamation policy.

Review Patrick J. Erger
(Signature)

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Executive Summary

For water managers, having good stream flow depletion data is critical to keeping accurate water balance equations to inform the allocation decision process. The Great Plains Region (GP) has dealt with this issue in the Missouri River Basin by developing a model, known as Missouri River Basin Depletions Database (MRBDD), which calculates the stream depletions, by reach, using actual irrigated acres and crop water requirement calculations. The crop water requirements are then used to produce the reach depletions attributable to agricultural diversions. GP has been improving this model for the past two decades, and currently has an adequate model of the Missouri River Basin. However, since the original development of the model, the following factors have resulted in some concern as to whether the model is sufficiently advanced for modern planning purposes.

- The equations used in the model do not reflect the state of the art in crop coefficient calculations.
- Climate change has become a large part of the planning process.
- GP has realized this model could be generalized to work in other basins.
- Considerable interest in the model from outside agencies has been observed, indicating this model could be beneficial to a wider audience.

Therefore, GP sought to scope a project to update, upgrade, generalize, and distribute this model so that it can be used for processing historical depletions and Global Climate Model (GCM) outputs to analyze the changes in stream flow depletions resulting from modeled climate scenarios and historical water use. This would further water rights planning, in stream flow planning for fish and wildlife, yield analyses for reservoirs, water availability analyses, and other resource planning efforts under both current conditions, and under climate change conditions.

Reclamation's Technical Service Center (TSC) Water Resources Planning and Support Group was contracted to conduct a review of the MRBDD with a view toward scoping a project to update, upgrade, generalize, and distribute this model.

Scope of the review in the Science and Technology Proposal:

- Task 1 – Perform a review of existing model to document its capabilities, data requirements and formats, and confirm the methods being used.

- Task 2 – Perform a literature review to determine what improved simulation methods, crop and climate data, data formats, and data input methods are available and feasible for inclusion into a revised model.

- Task 3 – Coordinate with local, State, and Federal entities to access the level, need for and uses of depletion data, data resources available, and willingness to assist in the project.

- Task 4 – Prepare a scope of work for development of a stream flow depletions analysis tool that evaluates net impact of stream diversions on stream flow, and which has broad applicability to meet Federal, state, and local needs.

TSC broke the above tasks into the following steps:

1. Review existing model. This was broken into three categories:
    a. Database
    b. Code
    c. Methods.

2. Literature review.

3. Consultation with basin MRBDD users and users of similar modeling systems.

4. Formulation of recommendations.

5. Implementation of minor modifications.

6. Report of findings and recommendations.

7. Scope future evolution of the MRBDD.

The MRBDD is technically sufficient for computation of historical depletions and has been adequate for application of its output to date. Minor changes could be made to existing methods to improve current use of MRBDD depletions. However, the MRBDD is mostly limited to computing historical depletions and is really limited as a tool to support other scenarios such as climate change alternatives. Furthermore, the MRBDD has a number of non-hydrology method deficiencies that require a revisit of the system design and a strategy for implementation of the revised design.

The MRBDD as a general tool for computation of depletions has limited interest elsewhere in Reclamation. Although the problems are common to all of Reclamation, the MRBDD application has a number of basin specific items. In addition, the system design deficiencies make the existing MRBDD problematic to maintain or to modify. A more robust design that is maintainable and supportable would create additional interest in other areas.

The biggest deficiency of the MRBDD system is the Access data store. The database needs to be redesigned as a relational database. The second biggest deficiency is code, both use of VBA and its residence in the data store. Numerous code revisions are in order but major code revisions are dependent upon selected design. The third biggest deficiency is data and methods used by the MRBDD. Inconsistency in CIR and soil moisture computations exists and large amounts of estimated and empirical data are involved in water supply estimates and depletion computations.

Work should begin on a revised design as soon as possible followed by formulation of an implementation strategy.

A number of the review's recommendations are high priority but require minimal resources to implement (collectively they would require moderate resources). Some recommendations can be done before a revised system design is finalized and formulating an implementation strategy. This effort should also help inform system design and implementation strategy. However, some recommendations are redundant, require more resources, or are design dependent and should not be tackled until revised system design is completed and implementation strategy is formulated.

Modifications to the MRBDD should be incremental. A suggested approach is to clone existing database, start implementing design independent recommendations while selecting a revised design, borrow database example code from other database capable applications, and start prototyping of MRBDD code in VB.net. Alternatively, existing code could be separated from database before migration to VB.net. If decision is made to move to a daily time step, the data would have to be moved to another database engine because of Access limitations. However, very little code would have to be modified related to moving to another database engine because database communications would be similar.

Based on the TSC review, an overall recommendation and numerous individual recommendations were formulated. The overall recommendation is to separate the MRBDD into distinct pieces. This would allow more autonomous maintenance of a system of components. For instance, one person could be responsible for maintenance of meteorological and hydrologic data, another for the other data, another person or organization such as TSC for the irrigation requirements model(s), and another for the depletions model. The meteorological and hydrologic data and other data could remain in a common data as it is presently in the MRBDD or be split into a time-series database and other data stores for the other data. This approach could be called something like the Missouri River Basin Depletions Data Management System (MRBDDMS).

An attempt was made to place individual recommendations into four major categories but some overlapping exists. Not all recommendations are exclusive because some recommendations will likely be implemented incrementally or not at all. That is, implementation of one recommendation may alleviate need for another recommendation. In addition, some recommendations may not be feasible for technical or financial reasons.

Evolution of the MRBDD could be viewed in terms of good, better, and best. A good system would include:

- Separation of code from database
- Redesign of meteorological and hydrology tables
- Separation of CIR and soil moisture accounting from reference ET computations (and by extension, use of ET methods that compute reference ET) with common CIR and soil moisture methods for entire basin.

- Revision of code to type all variables and to use more readable names.
- Use of code specified SQL for data queries instead of entire table reads to query data.
- Posting of selected output data to database with reporting done as a post process instead of on the fly.

A better system would include:

- Redesign of other data (crop mixtures by year, etc.) time-series tables.
- Separation of irrigation requirements computations from depletion computations, allow use of parameter specific models that can be maintained independently.
- Ability to support climatic and hydrologic scenarios.

The best system would include:

- Storage of meteorological and hydrology data in a database other than Access.
- Extension to a daily time step.

Appendix

RECLAMATION

Managing Water in the West

Technical Memorandum No. 86-68210-2014-04

Missouri River Basin Depletions Database Technical Service Center Review

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

September, 2014

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Missouri River Basin Depletions Database
Technical Service Center Review

Introduction

This document reports a review of the Missouri River Basin Depletions Database (MRBDD), a model used by the Bureau of Reclamation (Reclamation) Great Plains (GP) Region to estimate depletions by crop and public supplies in the Missouri River Basin. The review was conducted by Reclamation's Technical Service Center (TSC) Water Resources Planning and Support Group. GP Region wrote a Science and Technology (S&T) proposal that was source of funding for the review. TSC was contracted by the region to conduct the review.

Scope of the review in the S&T Proposal:

- Task 1 – Perform a review of existing model to document its capabilities, data requirements and formats, and confirm the methods being used.
- Task 2 – Perform a literature review to determine what improved simulation methods, crop and climate data, data formats, and data input methods are available and feasible for inclusion into a revised model.
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TSC broke above tasks into following steps:

1. Review existing model. This was broken into three categories:
    a. Database
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3. Consultation with basin MRBDD users and users of similar modeling systems.
4. Formulation of recommendations.
5. Implementation of minor modifications.
6. Report of findings and recommendations.
7. Scope future evolution of the MRBDD.

Following pages are a report of TSC's review and findings, recommendations, and conclusions.

Review

Overview

The existing MRBDD consists of a Microsoft Access system comprised of following components:

1. Parameter data tables – Database tables in which mostly non-temporal parameter data are stored.
2. Non-meteorological data time-series tables – Database tables in which non-meteorological time-series data such as crop mixtures, irrigation practices, and other time varying data reside.
3. Meteorological data tables – Database tables in which meteorological time-series data reside.
4. Forms – Menus to direct computation, select data entry forms, and to perform data entry. Forms typically have some code associated with them for managing responses to user selections.
5. Code Modules – Where non-form code is resides. Non-form code is the numerical model associated with the MRBDD.
6. Queries – Database queries of selected tables that support forms and code.
7. HUCs - MRBDB geographic computation unit - HUC8's (aka called HUCs).

Data and Methods

The MRBDD currently uses following categories of data:

1. Crop areas by county developed from United States Department of Agriculture (USDA) Ag Census and Ag Statistic reports supplemented by some state provided data.
2. United States Geological Survey (USGS) Water Supply Reports (non-irrigation water use).
3. Mapping of counties to HUCs.
4. HUC surface water verses ground water sources of supply inventory.
5. HUC irrigation practices and efficiencies.
6. Empirically derived data to support ET methods (percent daylight hours for Blaney-Criddle and Solar Radiation for Jensen-Haise).
7. Meteorological data (average monthly temperature and monthly precipitation).
8. Known and heuristic (rule-of-thumb) data for estimating water supplies.

Evapotranspiration (ET) and Crop Irrigation Requirement (CIR) in the MRBDD are computed using either the Blaney-Criddle method or the Jensen-Haise method, depending on the state. Both methods are dated. Blaney-Criddle uses entirely empirical equations. At least three Blaney-Criddle methods exist – Original, Modified, and FAO[1]. The MRBDD uses the Modified Blaney-Criddle method as documented in Appendix A of National Resource Conservation Service (formerly Soil Conservation Service) publication TR-21 (SCS, 1990). Original and Modified Blaney-Criddle do not compute reference ET whereas FAO Blaney-Criddle and Jensen-Haise do compute reference ET[2]. The Jensen-Haise reference ET computation involves calibration of empirical coefficients. FAO Blaney-Criddle requires additional meteorological data.

Blaney-Criddle and Jensen-Haise (as well Hargreaves-Samani and other methods) are called temperature methods because their only temporal input data requirement for computation of ET is temperature[3]. Newer computation methods such as Penman-Monteith use a pseudo energy balance in computation of ET and are preferred from a scientific standpoint. However, these methods also require wind, dew point or humidity, and solar radiation which often are unavailable in many locations or availability is limited. In general, temperature methods are more sensitive to changes in temperature[4].

TSC's Penman-Monteith model[5], developed by the University of Idaho, Desert Research Institute, and TSC, currently only computes using daily timestep but could partially[6] be extended to a monthly timestep. It has ability to estimate solar radiation, wind, and dew point temperature, thus making its required input data the same as the MRBDD's. It includes the American Society of Civil Engineers (ASCE) standardized methods for computing reference ET (ASCE, 2005) as well as a dual crop curve approach for computing soil evaporation separately from crop transpiration (Allen, et al, 2005). Data for estimating solar radiation, wind, and dew point temperature were developed for the West-wide Climate Change Risk Assessments (WWCRA) study (Reclamation, 2014).

ASCE's standardized methods (grass or alfalfa Penman-Monteith based reference ET) are preferred approaches for ET estimation. NRCS recommends use of FAO Blaney-Criddle to compute irrigation requirements when designing an on-farm irrigation system unless daily irrigations are required in which

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[1] TSC version of Blaney-Criddle can compute either Original or Modified Blaney-Criddle. FAO Blaney-Criddle is also known as Doorenbos and Pruit method and FAO Modified Blaney-Criddle.

[2] Most evapotranspiration methods developed since Blaney-Criddle use a two-step approach whereby an ET is computed for a reference crop such as grass or alfalfa and ET of all other crops is computed as a function of the reference ET. Blaney-Criddle computes crop by crop ET in one equation.

[3] Both Jensen-Haise and Hargreaves-Samani use solar radiation if provided but otherwise estimate solar radiation . Precipitation is required for soil moisture accounting and computation of crop irrigation requirement.

[4] In addition to computation of historical NIR's, temperature method ET models may respond differently to synthetic meteorology such as climate change scenarios.

[5] The Penman-Monteith method is only computation of reference ET. The model includes a crop module for computation of crop by crop ET and CIR and an area module for computation of crop weighed ET and CIR.

[6] Reference ET computations could easily be converted to monthly. However, crop ET and CIR computations are problematic to convert to monthly.

case they recommend using Penman-Monteith. Computation of irrigation requirements for hydrologic modeling probably should use something more sophisticated. Nonetheless, computation of crop by crop irrigation requirements is an inexact science that requires calibration. Solar radiation and crop calibration were done for the WWCRA study in the Missouri River Basin.

A daily timestep would be problematic for the MRBDD. Although daily ET computations could be facilitated and would improve ET and CIR computations, the data used for the hydrologic computations (water supply, return flow, and depletion) are probably insufficiently precise to justify moving to a daily timestep. However, perhaps a hybrid system could be developed that computed daily irrigation requirements that are temporally aggregated to monthly for use with hydrologic (depletion) computations

ET models compute ideal irrigation requirement. Beneficial depletion is the portion of irrigation requirement that is supplied sufficiently enough to be consumed. Irrigation (beneficial) depletions in the MRBDD are the shorted area weighted crop irrigation requirement plus delivery loss which are determined by several empirical supply factors. Because these data are limited and empirical, it limits how well the MRBDD can estimate water supply, and thus depletion. In addition, other estimated and empirical data are used to compute non-beneficial consumptive use--depletion of irrigation diversions by non-crop evaporation and transpiration, also known as incidental losses. Reported depletion from the MRBDD is the sum of beneficial and non-beneficial depletion.

The MRBDD uses recorded meteorological data obtained of National Oceanic and Atmospheric Administration (NOAA) cooperative (Coop) stations. Most of those data were obtained using a commercial data provider. Those data are now available for free from several web sites.

Meteorological data frequently do not exist for entire simulation period of the MRBDD (1929-present[7]). Missing data in the MRBDD use adjacent stations for filling data. Although most of the basin is relatively flat, regression and statistical based data filling methods are preferable. Furthermore, those approaches can be automated and reduce maintenance requirements.

Recorded crop data, irrigation practices data, and supply factors do not exist for a good portion of the MRBDD's simulation period or are spotty in nature. Typically, linear interpolation is used to fill missing data for these periods. Although GIS data could potentially be used for extension of the simulation period forward, it will not help with older periods.

Although innovative in terms of computations, use of sixteen common irrigation practices is problematic in terms of data maintenance and cataloging. Inventories of irrigation practice are more typically cataloged by canal or other irrigation unit rather than by HUC. In addition, the design of the data tables that are associated with irrigation practices is not easily extended to additional practices such as localized irrigation (SCS, 1990).

[7] Latest data in the MRBDD is through 2007.

Data and methods used by the MRBDD are similar to those used in other Reclamation river basins. For instance, the Colorado River basin's Consumptive Uses and Losses (CU&L) Report[8] computes basin depletions using Original or Modified Blaney-Criddle method for irrigation depletions and USGS water supply report data for non-irrigation consumption. However, CU&L uses streamflow data to adjust for water supply. Shorted depletions are a function of when streamflow reaches threshold flows at specified gages based on a 1960's NRCS study. Although these data are unavailable for the MRBDD, it suggests that other alternatives for estimating water supply may exist. Some of these are discussed in the recommendations.

USDA Ag Census and Ag Statistics data are notoriously poor data. CU&L modelers supplement their crop area data with remotely sensed GIS type data when it is available[9]. USDA now produces the Cropland Data Layer (CDL) GIS coverage which is an inventory of all cropland in the United States. Although it does not distinguish irrigation from non-irrigated crops, it may be possible to use these data to supplement other USDA data.

Soil moisture and effective precipitation are computed for Jensen-Haise ET states but only effective precipitation is computed for Blaney-Criddle ET states. Blaney-Criddle ET states use the SCS effective precipitation method (SCS, 1990) on a crop by crop basis. Jensen-Haise ET states use an effective precipitation method of unknown origin[10] that is computed on a HUC basis and applied to each crop. In reality, the method used by the Jensen-Haise method is an infiltration method. The value is subsequently used in crop by crop soil moisture accounting.

The CIR adjustment factor (CIRFAC in code) is computed as a function of average of simulation period. This is problematic for synthetic meteorological data because if the factor is a function of average historical CIR, then model has no access to that number.

Return flow lagging coefficients are common to all HUCs of the MRBDD.

Reservoir evaporation is not computed by the MRBDD.

The MRBDD does not account for imports and exports, also known as transbasin diversions.

Some data are set in code (aka hard-wired).

Database

The biggest problem with the MRBDD is that it is not structured as a relational database (RDB). A properly designed RDB enables efficient use of Structured Query Language (SQL) to query data from the

[8] CU&L report is produced on a five-year cycle. Depletions have computed been computed annually in recent years.

[9] Colorado basin GIS data for New Mexico and Colorado became available in early 1990's.

[10] It is similar to the "Reclamation" effective precipitation method available in TSC's Blaney-Criddle application.

database, making it readily available to forms, code, reports, applications and users. The predecessors to the MRBDD used text (aka ASCII) files for data storage and Fortan code for modeling. The MRBDD essentially replicates that system, including the formats in large part, in an Access file. That is, the tables in the Access data store[11] have most of the same limitations that the text based system had because RDB principles were not followed. This creates database integrity problems, maintenance problems, and modeling problems. Two examples of major deficiencies in database design are provided.

Non-meteorological time-series tables are in the MRBDD typically have attributes (aka fields or column names) as shown on Figure 1.

tbl_SW_PublicSupplyConsumed

HUC	1929	1930	1931	1932
10090204	0.035	0.036	0.036	0.036
10090205	0.000	0.000	0.000	0.000
10090206	0.285	0.286	0.287	0.288
10090207	0.001	0.001	0.001	0.001
10090208	0.000	0.000	0.000	0.000
10090209	0.000	0.000	0.000	0.000
10090210	0.000	0.000	0.000	0.000

Record: 292 of 310 No Filter Search

Figure 1. Example existing non-meteorological time-series table.

A properly designed RDB table's design would be something as shown on Figure 2.

ZSW_PublicSupply

HUC	Year	the_value
10020004	1993	0.415
10020004	1994	0.416
10020004	1995	0.417
10020004	1996	0.419
10020004	1997	0.420
10020004	1998	0.422
10020004	1999	0.423
10020004	2000	0.425

Figure 2. Example revised non-meteorological time-series table.

[11] TSC reviewer hesitates to call the MRBDD a database.

The latter design enables more efficient use of SQL, is automatically extendable for additional years, and is normalized. Normalization is designing a database to optimize queries of the database using SQL and includes built-in consistency checks between database tables (database integrity).

Meteorological time-series tables are in the MRBDD typically have attributes as:

Year

January value

February value

March value

…

December value

Every meteorological time-series[12] is stored in a separate table, making the database difficult to navigate, query and maintain. A properly designed database would use one table for all data of a given timestep and would be structured something like:

Node Id

Attribute Id

Date

Value

If scenarios are modeled, another attribute would exist which is a unique identifier for the scenario such as a scenario_id. A fully normalized RDB would combine the Node Id and the Attribute ID into a combined identifier.

Another deficiency in the MRBDD is use of Microsoft Access. Access has limitations on size that were not rectified when Office 2007 increased Excel limits. If the GP region elected to move the MRBDD to daily computations, an Access database would not hold all of the basin's data. Microsoft's Foxpro and

[12] The MRBDD is currently a monthly timestep model.

SQLServer database engines[13] are better suited for enterprise database development as well as are Oracle[14] and several free database systems.

Code

The object model in Office has remained the same for several years because of Microsoft's evolution of Visual Stuidio.Net at the expense of Office's programming language Visual Basic For Applications (VBA). Microsoft intends to stop supporting VBA at some juncture[15]. In addition, the Database Object Reference (DAO) technology being used by the MRBDB was replaced by ADO (Active-X for Data Objects) technology after Office 2000.

It is poor programming practice to store an application in the data store[16]. Modeling code should be developed and maintained independently of the data store so that both can evolve without being dependent upon the other. Since all modern coding languages can communicate with an RDB using SQL, separation of code from data store enables more flexibility in selection of a coding language. A properly designed RDB can usually be moved from one database system to another fairly easily. For instance, Access provides an "upscaling" utility to move data into SQLServer or Oracle.

TSC has converted several applications from VBA and VB6 (a close relative of VBA) to Visual Basic.Net (VB.Net), one of the programming languages provided with Visual Studio.Net. Conversion of non-form code is straightforward. Furthermore, TSC already has VB.Net versions of Blaney-Criddle, Hargreaves-Samani, and Penman-Monteith methods. It would be easy to create a VB.Net version of the MRBDD's Jensen-Haise method to the Penman-Monteith reference ET module. In addition, the VB.Net version of Blaney-Criddle can already communicate with Access tables of various designs whose code could easily be made available to other models[17].

Some hard-wired data (in particular, crop curve data and solar radiation factors.) exist in code.

Another issue with code is evolution from Fortran to VBA. Fortran programmers were limited to a length of eight upper case characters for variable names. For the most part, the converted code in the MRBDD uses the same limited variable names. Longer, mixed case variables names should be used to make code more readable. It should be noted that the TSC Blaney-Criddle code of the MRBDD has common ancestry with TSC's Blaney-Criddle model and uses readable variable names.

Another issue with code conversion is use of "go to" statements which are poor programming constructs.

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[13] The software system of a database system is called a database engine. The tables are the actual database.

[14] Reclamation has an organization license for Oracle.

[15]Microsoft originally scheduled ending support of VBA in 2011 but has not net ended support.

[16] RDB's often use code called stored procedures that are stored in the database that facilitate secured data loading and queries and data maintenance. Stored procedures are not intended for modeling.

[17] VB.Net Blaney-Criddle could readily be modified by TSC for use by the MRBDD.

Code modules are not named, making it problematic to know what module is doing what computations. Most subroutines and functions in the MRBDB are poorly named. Most variables types are undeclared.

Modeling code is unable to properly or efficiently use SQL because of database design deficiencies.

Recommendations

Based on review, an overall recommendation and numerous individual recommendations were formulated. The overall recommendation is to separate the MRBDD into distinct pieces as shown on Figure 3. This would allow more autonomous maintenance of a system of components. For instance, one person could be responsible for maintenance of meteorological and hydrologic data, another for the other data, another person or organization such as TSC for the irrigation requirements model(s), and another for the depletions model. The meteorological and hydrologic data and other data could remain in a common data as it is presently in the MRBDD or be split into a time-series database and other data stores for the other data. This approach could be called something like the Missouri River Basin Depletions Data Management System (MRBDDMS).

An attempt was made to place individual recommendations into four major categories but some overlapping exists. Not all recommendations are exclusive because some recommendations will likely be implemented incrementally or not at all. That is, implementation of one recommendation may alleviate need for another recommendation. In addition, some recommendations may not be feasible for technical or financial reasons.

Each of the individual recommendations includes a priority from 1 to 10, with 10 assigned highest priority, and a resource factor from 1 to 10, assuming 1 requires least resources. For instance, P8, R2 is a moderately high priority item that takes relatively few resources to implement. Resource factors are a function of implementation time and implementation difficulty.

Following individual recommendations are made.

Data

1. Incorporate WWCRA meteorological data and stations. The WWCRA's synthetized historical monthly data (aka Maurer Observed) can be extended forward from 1999 using same procedures used for the WWCRA and extended backward from 1950 using systematic data filling methods (P8 R1).

2. Incorporate WWCRA soils data (P5 R1).

3. Use Excel workbooks that have same structure as equivalent database table to develop non-meteorological data. This makes data more accessible, alleviates need for editing forms, and can easily be posted to database using Excel VBA[18] (P5 R2).

[18] Long-term, code for updating database could reside in revised code application or a Visual Studio Technology for Office (VSTO) application. VSTA is intended replacement for Office VBA.

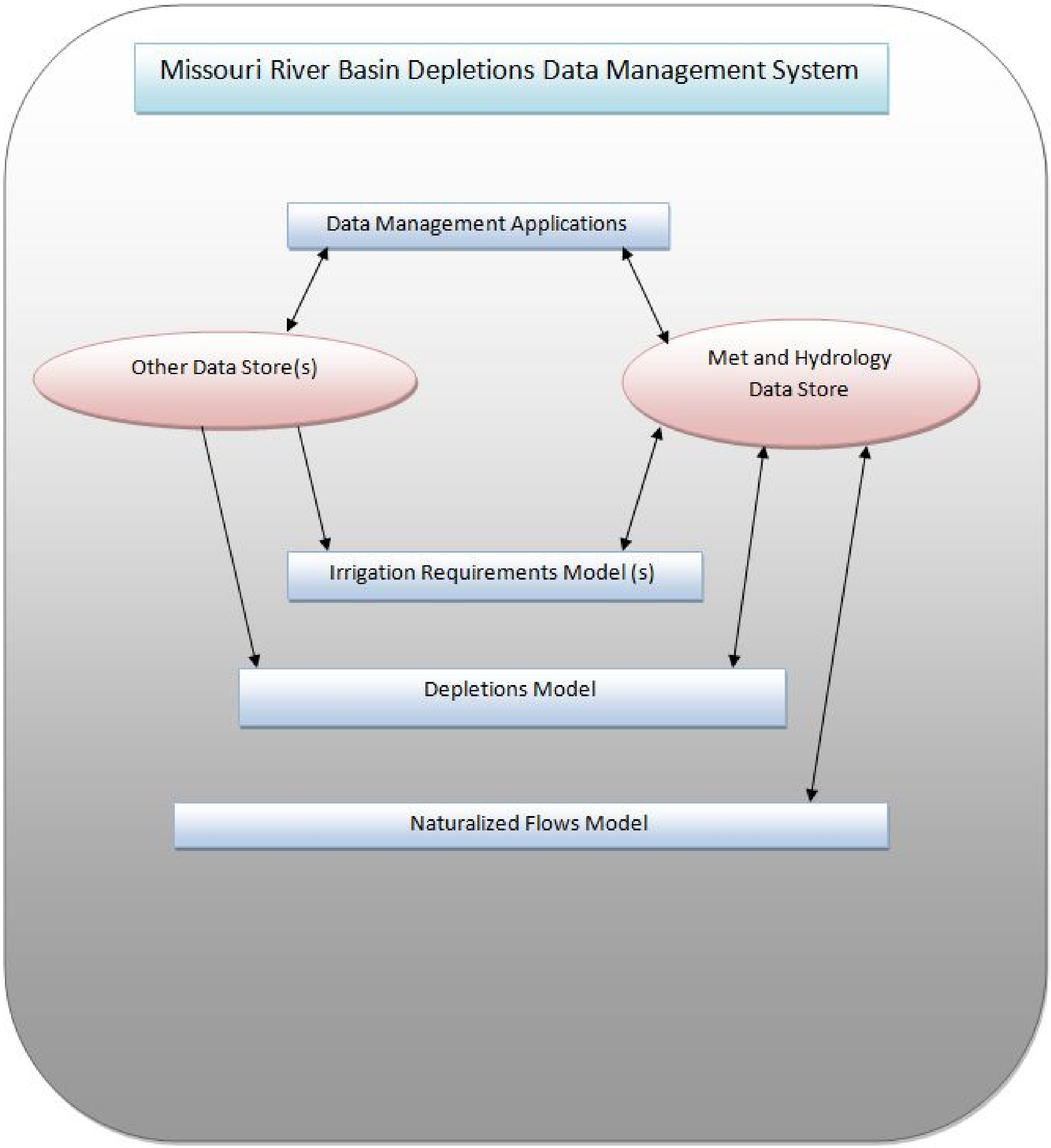

Figure 3. Data Management System Approach.

4. Procedures used to update meteorological and hydrological data should be revised. All meteorological and most hydrologic data are now available on-line or from Reclamation data servers. Applications such as TSTool, available from the Open Water Foundation[19], exist to facilitate automated data acquisition (P9 R5).

5. Use automated data filling methods for meteorological data. TSTool is a free application that has data filling capability (P9 R5).

6. All temporal data should be distinguished by recorded verses filled or estimated (P9 R5). This also facilitates scenario management (see Database section).

7. Develop return flow lagging coefficients specific to HUC. The routing (lagging) method used by the MRBDB is often called the impulse response method. The routing coefficients can be developed from well pump test transmissivity data where available. State of Colorado has developed lagging coefficients for entire state including Platte River, a tributary of the Missouri River[20] (P5 R8).

8. Use other hydrologic data such as streamflow, diversions, and reservoir releases to canals that are available on-line[21] or from the GP Hydromet system. These data should be used to inform water supply estimates for surface water supplies (P7 R7).

9. Incorporate other sources of cropping data such as GIS coverages into crop inventories (P7 R8).

10. Refine drought factors using other data sources. Consider using three categories – average, wet, and dry in lieu of existing two categories (P5 R5).

11. If ET methods are revised that need to have wind and dew point data, incorporate WWCRA average monthly wind and dew point depression data[22] (P5 R1).

12. Move hard-wired data and computation options from code into database or a model control file. For instance, use of present-level (last year available) for surface water ground water depletion factors is hard-wired in July, 2012 copy of code. This should be made into a user supplied option (P10 R1).

13. Update data annually to maintain in-house skills, to incorporate latest data, data access methods, and data management technology, and to extend knowledge base (P5 R2).

[19] Open Water Foundation - http://openwaterfoundation.org/

[20] Colorado Decision Support System - http://cdss.state.co.us/basins/Pages/SouthPlatte.aspx

[21] Recorded and estimated monthly Colorado canal diversions are available from 1909 at http://cdss.state.co.us/Pages/CDSSHome.aspx.

[22] TSC UI DRI estimates dew point from minimum temperature and average monthly dew point depression.

Database

14. Redesign entire schema to use standard RDB design practices such as normalization (P10 R6).

15. Move existing meteorological data into one table designed for optimized queries, data integrity, and easier maintenance. This would include a date attribute (aka field or column name) (P0 R5).

16. No data should be used as column names in database tables. For instance, a number of tables use the year's value as an attribute name. Besides being poor table design, they are problematic for data maintenance. Table designs should be independent of temporal variation. All tables that have temporal data, including crop mixture tables, should be designed as time-series tables. Data that vary on an annual basis can use an annual time-series date column and have other attributes specific to the table (P10 R5).

    A time-series crop mixture table would be able to handle varying crop types in the crop mixture. Existing system requires use of same set of crops for all HUCs.

17. Relations should be established between tables to facilitate database integrity and visualization of schema (P7 R1).

18. Post all relevant computed data into database. As a minimum, this should include area ET, non-shorted NIR, shorted NIR, estimated water supply and depletion. This facilitates ad hoc reports, archiving (in conjunction with scenario management) and cleaner code (P10 R5).

19. Implement ability to support multiple scenarios of both input and output data (P8 R5).

20. Move database (without code) to an enterprise database engine such as Oracle, SqlServer or any of a number of free database engines (P8 R6).

Code

21. Name and reorganize code modules to improve code accessibility[23] (P10 R1).

22. Improve memory management. For instance, all objects should be destroyed after they are no longer needed (P5 R1). For example:

    ```
    Set myObject = nothing
    ```

23. Remove meteorological station weighting from code since it is not being used.

24. Minimize use of global variables (also a memory management issue) (P5 R1).

25. Variable names inherited from Fortran should be changed to mixed case readable names (P9 R1).

[23] Completed by reviewer.

26. Variable types such as integer, double, boolean, variant, etc., should be declared for all variables to avoid mixed type computations and to prevent unintentional consequences of computations (P10 R1).

27. Boolean functions should be used in lieu of most subroutines to facilitate debugging (P0 R0).

28. Boolean variables should be used for all on/off flags (P9 R1).

29. Repair two bugs in Blaney-Criddle computations identified by TSC during conversion of TSC Blaney-Criddle to VisualBasic.net (P10 R1).

30. "Go To" statements, mostly left over from Fortran code, should be replaced with alternative logical constructions (P9 R2).

31. Create date variables and replace all existing time loops with date based loops. These should correspond to database query record sets from time-series tables (P10 R2).

32. Replace all DAO objects with ADO objects (P10 R2).

33. Except when actually used, replace all table wide queries with specific queries (P10 R1).

34. To extent possible, change reports from being output of computations to being reports of output data that is stored in database. Otherwise, place reporting code into a function (P10 R2).

35. Implement ability to support multiple scenarios of both input and output data (P9 R5).

36. Separate code from database and move to another programming environment (P9 R3). A logical destination would be to Visual Basic.net. This might be facilitated using an interim Excel VBA application.

Methods

37. Extend hydrologic (return flow and depletion) computations to use other data such as streamflow, diversions, and reservoir releases to canals (P7 R7). These data should be used to inform water supply estimates for surface water supplies. Whether it makes sense to develop pre-processed supply factors as currently used by the MRBDD or to incorporate these data into the depletion computations is an implementation issue beyond scope of this review.

38. Enable modelers more flexibility in specification of model setup and output (P6 R1). For instance, user should be able to select any year's crop areas as crop mixture for entire simulation.

39. Extend the MRBDD to include reservoir evaporation in depletion computations (P6 R6).

40. The CIR adjustment factor (CIRFAC in code) needs to be modified to support synthetic meteorologies (P7 R3). It either needs to be pre-processed or made to not be a function of average historical CIR).

41. Remove SCS effective precipitation method from Blaney-Criddle computations and use soil moisture accounting of Jensen-Haise computations for all ET methods (P8 R2). This would remove an inconsistency in computations and another source of uncertainty in output of the MRBDD. The steps should be:

    a. Compute HUC crop by crop ET using desired ET method.

    b. Use soil moisture accounting to compute HUC crop by crop and area CIR.

42. Consideration should be given to using other ET methods and to only using one ET method (P8 R4). Reasonable alternatives for a monthly timestep ET method are:

    a. Remove Modified Blaney-Criddle ET method and only use Jensen-Haise method.

    b. Replace Modified Blaney-Criddle ET method with FAO Blaney-Criddle ET method.

    c. Replace both Modified Blaney-Criddle and Jensen-Haise with Penman Monteith reference ET method but use Jensen-Haise crop ET methods.

    The TSC UI DRI TSC Penman-Monteith model can only compute daily crop ET but its reference ET method could easily be modified to support a monthly timestep and extended to optionally compute FAO Blaney-Criddle and Jense-Haise reference ET[24]. Reference ET from an extended Penman Monteith reference ET module could then be used with existing MRBDD's existing Jensen-Haise crop ET and soil moisture accounting code.

    Alternatively, a hybrid system could be developed whereby irrigation requirements are computed on a daily basis and temporally aggregated to monthly for use in hydrologic computations. The feasibility of this approach depends on availability of sufficient daily meteorological data prior to 1950[25] and ability to use another database engine. Using either alternative, the Penman-Monteith model's wind, dew point temperature and solar radiation estimation methods could be used.

43. Consideration should be given to using an independently supported ET model (P8 R4). This would remove a significant portion of code maintenance from the MRBDD and allow GP resources to focus on Missouri River Basin needs.

[24] The reference ET module of the Penman-Monteith module exists in both VB.net and VBA. The VBA code could be useful in an incremental evolution of the MRBDD code.

[25] Daily meteorological data for the WWCRA were developed from 1950 through 1999 and could be extended through 2010. However, those data can not be extended back to 1929 using the same data source (Maurer observed).

44. Consideration should be given to separating the irrigation requirement computations from the depletion computations (P7 R5). This would make ET method computations independent of hydrologic (depletion) computations.

45. Consideration should be given to using a generalized modeling system such as RiverWare for computation of depletions (P7 R10). Because the MRBDD is basically a linked list model (upstream HUCs to downstream HUCs), it is feasible to build a generalized model programmatically[26]. Using this approach, irrigation requirements would be computed as a pre-process and imported into hydrologic model. Then, water supply, return flows, and depletions would be computed by the hydrologic model.

46. Consideration should be given to computing irrigation requirements and depletions by more district nodes such as canals in lieu of HUCs which could be spatially aggregated to HUCs for reporting purposes (P7 R10). This would alleviate need to aggregate irrigation and conveyance efficiencies to HUCs.

47. Consideration should be given to moving code of the MRBDD into Visual Basic.Net (VB.net), one of the programming languages that are available from Visual Studio.Net (P8 R4). TSC has a Hargreaves-Samani module whose code is VB.net and whose data reside in an Access database. This application could be cloned for both example code and for implementation code for the MRBDD. The application also has communication with Excel and an Excel application has communication with the Access database, making the application robust in terms of data management. Primary advantage of this approach is that much of the data management code would exist or have prototypes and conversion of MRBDD code would be facilitated.

48. Include reservoir evaporation in depletion computations (P7, R7). This would also require modeling of reservoirs to some degree.

[26] San Juan Basin RiverWare model was built programmatically.

Uncertainty

Depletions from the MRBDD are used by the USGS in computation of naturalized flows and by Reclamation and the Corps of Engineers (COE) in operations and planning studies. USGS would like to get a handle on uncertainty that is associated with MRBDD depletions. Although not an expert in this arena, reviewer has following opinions based on forty years of experience. Biggest source of uncertainty is estimated water supply. Second largest source of uncertainty is efficiencies and other data that effect depletion computations. Irrigation requirements are smallest source of uncertainty for a given HUC. However, because two irrigation requirements methods are being used, it increases overall uncertainty. Implementation of a common irrigation requirements method would reduce uncertainty of the MRBDD.

Conclusions

The MRBDD is technically sufficient for computation of historical depletions and has been adequate for application of its output to date. Minor changes could be made to existing methods to improve current use of MRBDD depletions. However, the MRBDD is mostly limited to computing historical depletions and is really limited as a tool to support other scenarios such as climate change alternatives. Furthermore, the MRBDD has a number of non-hydrology method deficiencies that require a revisit of the system design and a strategy for implementation of the revised design.

The MRBDD as a general tool for computation of depletions has limited interest elsewhere in Reclamation. Although the problems are common to all of Reclamation, the MRBDD application has a number of basin specific items. In addition, the system design deficiencies make the existing MRBDD problematic to maintain or to modify. A more robust design that is maintainable and supportable would create additional interest in other areas.

The biggest deficiency of the MRBDD system is the Access data store. The database needs to be redesigned as a relational database. The second biggest deficiency is code, both use of VBA and its residence in the data store. Numerous code revisions are in order but major code revisions are dependent upon selected design. The third biggest deficiency is data and methods used by the MRBDD. Inconsistency in CIR and soil moisture computations exists and large amounts of estimated and empirical data are involved in water supply estimates and depletion computations. Work should begin on a revised design as soon as possible followed by formulation of an implementation strategy.

A number of the review's recommendations are high priority but require minimal resources to implement (collectively they would require moderate resources). Some recommendations can be done before a revised system design is finalized and formulating an implementation strategy. This effort should also help inform system design and implementation strategy. However, some recommendations are redundant, require more resources, or are design dependent and should not be tackled until revised system design is completed and implementation strategy is formulated.

Modifications to the MRBDD should be incremental. A suggested approach is to clone existing database, start implementing design independent recommendations while selecting a revised design, borrow database example code from other database capable applications, and start prototyping of MRBDD code in VB.net. Alternatively, existing code could be separated from database before migration to VB.net. If decision is made to move to a daily timestep, the data would have to be moved to another database engine because of Access limitations. However, very little code would have to be modified related to moving to another database engine because database communications would be similar.

Evolution of the MRBDD could be viewed in terms of good, better, and best. A good system would include:

- Separation of code from database
- Redesign of meteorological and hydrology tables
- Separation of CIR and soil moisture accounting from reference ET computations (and by extension, use of ET methods that compute reference ET) with common CIR and soil moisture methods for entire basin.
- Revision of code to type all variables and to use more readable names.
- Use of code specified SQL for data queries instead of entire table reads to query data.
- Posting of selected output data to database with reporting done as a post process instead of on the fly.

A better system would include:

- Redesign of other data (crop mixtures by year, etc.) time-series tables.
- Separation of irrigation requirements computations from depletion computations, allow use of parameter specific models that can be maintained independently.
- Ability to support climatic and hydrologic scenarios.

The best system would include:

- Storage of meteorological and hydrology data in a database other than Access.
- Extension to a daily timestep.

References

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United State Department of Agriculture, Soil Conservation Service (SCS), Part 623 National Engineering Handbook, 1990, Chapter 2 – Irrigation Water Requirements.

United State Department of the Interior, Bureau of Reclamation (Reclamation), Technical Memorandum No. 86-68210-2014-01, 2014, “West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Irrigation Demand and Reservoir Evaporation Projections.”

Glossary

Reference Evapotranspiration – Evapotranspiration of a reference crop, usually alfalfa or grass hay, that is used for estimating the ET of other crops using crop curves. Reference ET is often called potential ET.

Irrigation Water Requirement (IWR) – Water required in addition to precipitation needed to obtain desired crop yield and to maintain a salt balance in root zone (SCS, 1990).

Crop Irrigation Requirement (CIR) – Supplemental water needed for a crop to reach its potential evapotranspiration. CIR is usually expressed as a rate (length/time). Mathematically, it is defined as:

CIR = CET – CEP

where CET is crop (potential) evapotranspiration and CEP is crop effective precipitation. CIR is also called net irrigation water requirement (NIWR[27]).

Net Irrigation Requirement (NIR) – Supplemental water needed for all crops of an area to reach their potential evapotranspiration. NIR is the weighted crop irrigation requirement of an area and is computed as:

$$net\ irrigation\ requirement = \sum_{i=1}^{i=n} crop\ proportion\ i * cir\ i$$

where *n* is the number of crops in the crop mixture for an area, crop proportion *i* is the proportion of crop *i* total acreage for the area, and cir *i* is the NIWR rate for crop *i*. Volumetric rates (flow or volume/time) of NIR are computed as

$$Area\ NIR\ Flow = Area\ NIR\ rate * irrigated\ area$$

where *Area NIR Flow* is the volumetric rate of NIR. Area NIR flow is the non-shorted irrigation requirement due to crop needs.

Effective precipitation – That portion of precipitation that infiltrates soil and does not produce deep percolation. Because existence of a crop affects both infiltration and deep percolation, it is preferable to compute effective precipitation as part of a crop's soil moisture balance. Crop effective precipitation (CEP) is subsequently a function of a number of variables.

Depletion – Actual (aka shorted) amount of water consumed by crops, evaporation, and other consumers of water that is supplied by irrigation. In the MRBDD, depletion is sum of beneficial consumptive use (crops) and non-beneficial consumptive use, both supplied by irrigation. Depletion is usually expressed as a flow (volume/time). Beneficial depletion (consumed by crops) is the shorted Area NIR Flow; that is, the portion of the Area NIR Flow that was supplied by irrigation.

[27] Standard definitions for some terms do not exist. These definitions are for consistency in review. Reviewer prefers to use CIR for crops and NIR for areas.

Supply – Water that is available for irrigation. The portion of the supply that is actually diverted is called "diversion".

Apparent depletion – Depletion that "appears" to occur in current timestep[28]. It is mathematically defined as:

apparent depletion = diversion (aka supply) – routed (aka lagged) return flow

Immediate depletion – Depletion that immediately occurs (without lagging included) in current timestep. It is mathematically defined as:

immediate depletion = Diversion – immediate return flow

where immediate return flow is portion of return flow that occurs this timestep and diversion is diverted supply.

Full Service Irrigation – Supply of an area that that is not shorted.

Partial Service Irrigation – Supply of an area that that experiences shortages.

Gravity irrigation – An irrigation application method that delivers irrigation water from uphill (head) to downhill (tail) of a field using force of gravity. Includes furrow irrigation and water spreader irrigation.

Furrow irrigation – An irrigation application method that delivers irrigation water from uphill (head) of field via furrows. More generically called gravity irrigation.

Water spreader irrigation – An irrigation application method that delivers irrigation water from uphill (head) of field through spreading of water across field. Also called wild flooding and more generically called gravity irrigation.

Sprinkler irrigation – An irrigation application method that applies water using sprinklers from pressured pipes.

Center pivot irrigation - An irrigation application method that applies water using sprinklers hung from a large boom that rotates around a central pivot.

Localized irrigation - An irrigation application method that applies water to base of plants, usually through low-pressure pipes to specific crops. Applications are known as trickle, drip, drop, and mirco (SCS, 1990).

Irrigation Efficiency[29] – Efficiency of irrigation delivery on an individual farm or average of multiple farms of a collection such as all farms served by a common canal. Mathematically, it is:

irrigation efficiency = beneficially used water / on-farm irrigation delivery

Conveyance efficiency – Efficiency of irrigation system from point of diversion to irrigation delivery. Mathematically, it is:

conveyance efficiency = irrigation delivery / system diversion

[28] The MRBDD computes apparent monthly depletion. Apparent depletion and immediate depletion are same on an annual basis in the MRBDD.

[29] The MRBDD calls irrigation efficiency on-farm efficiency.

System efficiency – Combined conveyance efficiency and irrigation efficiency[30]. Mathematically, it is:

*system efficiency = irrigation efficiency * conveyance efficiency*

Hydrologic Unit Code (HUC) – A USGS[31] defined geographic area associated with a drainage basin. The standard HUC (HUC8's) have 8 digits that correspond to region, subregion, and unit.

[30] The MRBDD calls conveyance efficiency system efficiency. It appears to use conveyance efficiency correctly.

[31] http://water.usgs.gov/GIS/huc.html