Forest Thinning Management

Assessing Potential Water Quantity Improvements for the Miyun Reservoir in Beijing, China
June 2015

A Technical Primer on Quantifying Benefits of Watershed Interventions

Prepared by: "Andrew" Feng Fang, Ph.D.
Thomas Zimnicki
Mark S. Kieser

KIESER & ASSOCIATES
ENVIRONMENTAL SCIENCE & ENGINEERING

536 E. Michigan Ave, Suite 300
Kalamazoo, MI 49007 USA

Work supported by:

FOREST TRENDS

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Agency for Development and Cooperation SDC

The China Mega City Water Fund (CMCWF) for the city of Beijing is being developed in cooperation with the Beijing Forestry Society (BFS), China Biodiversity Conservation and Green Development Foundation (CBCGDF), International Union for Conservation Nature (IUCN), and Forest Trends. Once operating, the CMCWF will identify, fund, and help implement watershed improvement projects ("interventions") to benefit water quality and water quantity in the Miyun reservoir. The City of Beijing relies in part, on the reservoir as a critical drinking water supply. Efforts are underway to establish an operating framework for the Fund that can evaluate various watershed interventions in the context of relatively simple, established performance metrics for water quality and water quantity benefits. Coupled with projected costs for such interventions, the water fund will be able to assess, compare and optimize benefits associated with its investments in watershed improvements.

A notable challenge facing the CMCWF, and other water funds throughout the world, is the ability to reasonably estimate water quality and/or water quantity benefits associated with specific interventions. As such, this Technical Primer[1] represents an initial examination of quantification methods that the BWF and others may use to reliably estimate water resource benefits derived from particular land management interventions in the watershed of the Miyun reservoir. This approach relies upon existing studies from both the Miyun watershed and other basins in China.

Proposed Intervention: Forest Thinning

During the late 1990s, widespread desertification and landslides prompted the national government to afforest significant areas throughout China. Forests have long been thought to provide beneficial ecosystem services through soil stabilization and reduction in desertification[2,3] however, these services

[1] This Technical Primer was prepared by Kieser & Associates, LLC through Forest Trends of Washington, D.C. in collaboration with BFS and IUCN. Funding was provided by the Swiss Agency for Development and Cooperation SDC.
[2] Xie, X., S. Liang, Y. Yao, K. Jia, S. Meng, J. Li. 2015. Detection and attribution on changes in hydrological cycle over the Three-North region of China: Climate change versus afforestation effect. Journal of Agricultural and Forest Meteorology. 203: 74-87.
[3] Cao, S., L. Chen, D. Shankman, C. Wang, X. Wang and H. Zhang. 2011. Excessive reliance on afforestation in China's arid and semi-arid regions: Lessons in ecological restoration. Journal of Earth-Science Reviews. 104: 240-245.

may not actually result from afforestation.[4] Between 2000 and 2009, the Chinese government invested upwards of 725 billion RMB ($100 billion) to afforest a targeted 76 million hectares with the purpose of obtaining these aforementioned benefits. Increased forest cover also occurred as a result of other government-driven programs, notably the Sloping Land Conversion Program (or "Grain to Green") that converted approximately 15 million hectare of cropland to forest.[5]

Afforestation has led to several unintended ecosystem consequences. Most germane to this Technical Primer is the consequence of increased evapotranspiration (ET) from afforested lands. Estimation of ET rates on forested lands varies among published research. Studies that modeled estimated reductions of stream flow resulting from afforestation range from 50-300 mm/yr for northern and southern subtropical regions of China, respectively.[6] These quantities represent 10 to 50 percent of average pre-forestation flow rates. Worldwide data, as well as Northwest China specific data, indicate that reductions in water yield resulting from afforestation range from 50 to 60 percent.[3] Reductions in streamflow resulting, in part from afforestation, are of particular concern for Beijing. An expanding Beijing population that currently exceeds 20 million and grows by 250,000 annually places a significant strain on drinking water resources.[7] Current water supply and demand are approximately equal, 3.6 billion cubic meters.[6] Given the current strain on local water supply, an understanding of mitigating water yield losses resulting from afforestation may be of particular importance to the City.

Forest thinning is the targeted removal of trees and other vegetation in order to achieve the optimal ecological, economic, and social functions of a forest by promoting the growth and propagation of remaining tree species. Forest thinning is generally understood to have a positive effect on water yield.[8] Water yield may respond proportionally to area of coverage cleared.[9,10,11] Forest thinning is part of the so-called "close-to-nature" forest management being promoted and practiced in the Miyun Reservoir watershed, especially on young single-species forests established through afforestation. As such, the potential quantitative benefits of increased stream flow in the Miyun watershed are described herein for forest thinning as a watershed "intervention" (management practice) for increased quantities of stored water in the Miyun reservoir.

---

[4] Wang, Y., W. Xiong, S. Gampe, N. Coles, P. Yu, L. Xu, H. Zuo and T. Wang. 2015. A water yield-oriented practical approach for multifunctional forest management and its application in dryland regions of China. Journal of the American Water Resources Association. 51 (3): 689-703.

[5] Bennett, M. and J. Xu. Undated. China's Sloping Land Conversion Program: Institutional innovation or business as usual? Workshop on "Payments for Environmental Services (PES) -Methods and Design in Developing and Developed Countries."

[6] Sun, G., G. Zhou, Z. Zhang, X. Wei, S. McNulty, J. Vose. 2006. Potential water yield reduction due to forestation across China. Journal of Hydrology. 382:548-558.

[7] Wang, J. Y. Shang, H. Wang, Y. Zhao, Y. Yin. 2015. Beijing's water resources: Challenges and solutions. Journal of the American Water Resources Association. 51(3): 614-623.

[8] Bosch, J. M., and Hewlett, J. D., 1982, A Review of Catchment Experiments to Determine the Effect of Vegetation Changes on Water Yield and Evapotranspiration, Journal of Hydrology 55: 3-23.

[9] Bosch, J. and J. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on a review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology. 55: 3-23.

[10] Baker, M. 1986. Effect of Ponderosa Pine treatments on water yield in Arizona. Journal of Water Resources Research. 22(1): 67-73.

[11] Zhao, Yang, 2014, Runoff Evolution of Small Basins in the Miyun Reservoir Watershed under Changing Environment (PhD dissertation), Chapter 7, Beijing Forestry University, 2014.

Calculating Water Quantity Benefits

Forest thinning leads to several potential hydrological outcomes. For instance, thinning will reduce forest canopy density and in turn reduce evapotranspiration (ET) and precipitation interception, both of which ultimately increase local water supply with more water returning to streams. Conversely, reductions in canopy density will increase light availability and potentially promote understory vegetation which may result in water yield reductions. Differentiation between the relative effects of thinning for both reductions in ET and interception requires a substantial effort to detail hydrological relationships at each intervention site. The quantification methods described herein provide one approach to understanding the water supply benefits of forest thinning absent robust monitoring data. Application of these calculations at specific sites will ultimately benefit from a stronger understanding of hydrologic responses to forest thinning through future monitoring.

The approach to quantifying runoff volume yield benefits from thinning is developed, in part, using existing literature on forest thinning in the Banchengzi watershed. The Banchengzi Reservoir watershed (BRW) is an approximately 66 square kilometer watershed, 96% of which is forested, located roughly 12 kilometers north and upstream of the Miyun reservoir. Methods in this technical primer center on a linear relationship of unit area forest biomass and watershed stream runoff output on BRW.[11] Given the relative proximity to the Miyun, the linear equation derived for BRW is considered highly applicable for quantification methods in this primer. Other calculation approaches may be available, however, these would likely require field monitoring and additional research to assess their capability to quantify water supply improvements.

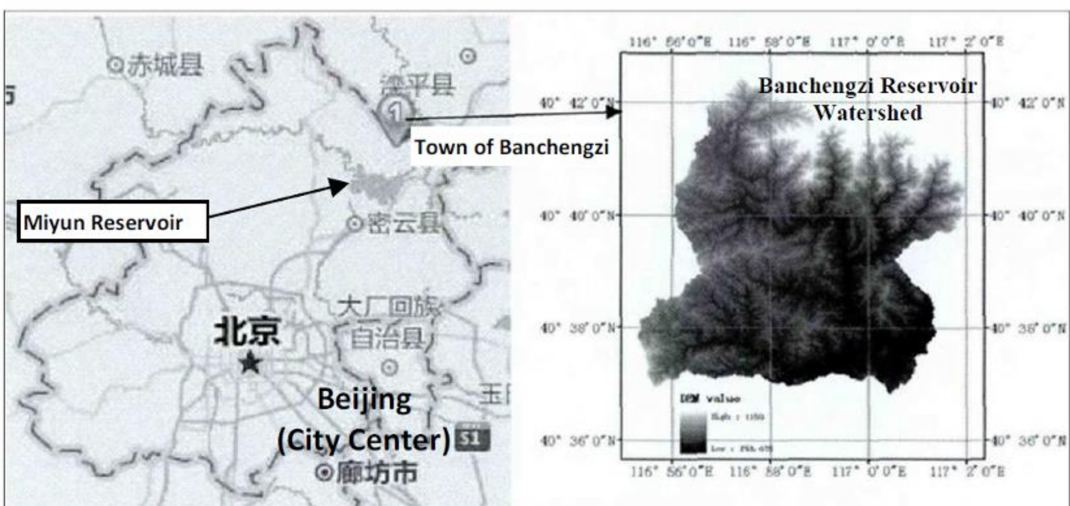

Figure 1: Map of Banchengzi watershed. Adapted from Zhao (2014).

The linear approach involves applying the runoff volume equation twice; first to represent conditions before the intervention and second to represent conditions after the intervention. The difference between these conditions reflects, in part, decreased ET and canopy interception and in turn the increased water yield.

The generalized steps used to estimate the water quantity benefits using this approach include:

A. Gathering necessary information

1. Annual precipitation (mm/yr)
2. Area of forest thinning implemented (hectares)
3. Forest biomass before forest thinning (ton/ha)
4. Forest biomass after forest thinning (ton/ha)

B. Calculate intervention benefits

1. Calculate baseline surface runoff depth before forest thinning (mm)
2. Calculate surface runoff depth after forest thinning (mm)
3. Calculate annual surface runoff volume change due to forest thinning (m^3/yr)

The following equations illustrate this proposed quantification method of runoff volume increase (yield) resulting from thinning. Detailed example calculations of Equations 1, 2 and 3 are provided as a hypothetical scenario in Attachment A of this primer.

Runoff volume is calculated based on forest biomass quantities as:

$$q = a \times w + b \quad \text{(Equation 1)}$$

Where:

q = surface runoff coefficient (mm flow/mm precipitation)
w = unit area forest biomass (ton/ha)
a and b = linear equation constants: -0.006 and 0.3013, respectively

From the surface runoff coefficient (q), runoff depth is calculated as:

$$Q = q \times P \quad \text{(Equation 2)}$$

Where:

Q = runoff depth (mm/yr)
P = annual precipitation (mm/yr)

The change in surface runoff coefficient (q) which results from a decrease in biomass associated with thinning is determined using Equation 1. To this end, Equation 1 is applied twice, once with current forest biomass value and again after the thinning operation. Runoff coefficient values are then entered into Equation 2 to obtain two runoff depth values. The difference (ΔQ) between both values is the surface runoff depth change due to forest thinning.

Equation 3 describes the step to convert runoff depth to runoff volume:

$$\Delta v = \Delta Q \times A \times \textit{Unit Conversion Factor} \qquad \text{(Equation 3)}$$

Where:

ΔV = runoff volume change due to forest thinning (m^3/yr)
ΔQ = runoff depth difference before and after forest thinning operation (mm/yr)
A = area of forest thinning (hectare)

Unit conversion factor = 10

Not considered in these computations are any water withdrawals or other losses between the outlet of the catchment with the forest thinning intervention and the Miyun Reservoir. These would need to be separately considered from Equations 1, 2, and 3. Assumptions specific to these equations are described in the next section of this Technical Primer as related to determining runoff volume improvements resulting from thinning for site applications. This final section highlights several key considerations and also provides recommendations for future improvement of this quantification method.

Future Methodological Improvements

Several assumptions are made with the proposed water quantity benefit application derived from Zhao (2014) to the Miyun Reservoir watershed. Future work using this method may benefit from additional research to identify site-specific conditions for Equation 1. Additional applicable considerations here are for forest biomass, scalability of the forest thinning practice and forest biomass rebound.

Site Specificity of Equation (1):
It is important to recognize that Equation 1 was developed based on data and observations for the BRW. The applicability of Equation 1 in other areas in the Miyun Reservoir Watershed (or any other water source areas for Beijing) should be examined during management practice implementation. Furthermore, Zhao (2014) developed a similar regression equation for a watershed east of the Miyun Reservoir where forest cover is lower (88.3% in 2010) and human activity is higher. For calculations in this latter watershed, equation constants varied considerably from those in BRW which may indicate the importance of geophysical and biological characteristics in forest management. Although current efforts will be focused in the BRW and thus the application of Equation 1 is appropriate, it will likely be necessary to adjust the linear equation constants when the equation is applied to new drainage areas.

Forest Biomass:
Forest biomass, as used in Equation 1, includes forests dominated by either trees or shrubs. When calculating forest biomass in the BRW, Zhao (2014) utilized calculation methods developed for various tree and shrub species in Beijing's mountainous areas. These methods were based on field measurements and relied on the height and diameter of individual trees for each species and the unit area biomass for shrub species. Whenever possible, this approach should be applied to quantify forest biomass change due to forest thinning when Equation 1 is used. Other measurements, such as growing wood stock used in the close-to-nature forest management[12], can also be applied if proper conversion between forest biomass and growing wood stock is made.

Scalability:
Equation 1 was derived based on the BRW, a watershed of 66.1km^2. Any initial thinning operation implemented by Beijing Forestry Society would likely cover an area notably smaller than the BRW and concentrated in the treatment area. Therefore, it is recommended that hydrologic data (precipitation and stream flow) from the treatment area be collected to verify the calculated values are not altered by watershed area. Equation 1 may be modified to accommodate new information on the area and its effect on water yield.

Biomass Rebound:

[12] Miyun County Forestry Department and Beijing Forestry Survey and Design Institute, 2008, Forest Management Plan (2008-2017) in Huayuannangou, Xinchengzi, Miyuan County, Beijing, March, 2008.

A reasonable assumption is that a mature forest (multiple tree types, species, appropriate age structure, total biomass) is able to maintain at a near constant level of water yield with limited human influence. However, since much of the area has been recently forested, the average age of tree stands is relatively low and likely uniform. For example, in the Miyun Reservoir drainage area, 41% of forests are under 10 years old, 24% range from 10 to 20 years and only 20% are between 20 to 30 years.[13] Given these age demographics, it is conceivable that removed biomass from thinning would be quickly replaced by remaining trees in the area. If this occurred and the increased growth of the remaining trees took up the additional water from thinning, the overall benefit to water yield would be diminished. For example, research in ponderosa pine forests in Arizona, U.S., showed that water yield increase became negligible after 6 years of thinning of the forests by 30% (basal area reduction) or less.[14] However, the hydrologic effect on watershed water yield of transition from a monoculture young forest to a better or close-to-nature structured forest by thinning has not been well studied. Continuous monitoring of the forest biomass and water yield is thus crucial to understanding the long term effect of forest thinning in BRW. Such monitoring could then be used to better justify equation applications.

Monitoring:

Given the potential physical, and consequently quantified variability between sites, it is recommended to perform post-operation data collection for method verification, calibration or equation refinement. Zhao (2014) developed Equation 1 using 19 years of observed annual stream flow data at the inlet of the Banchengzi Reservoir, precipitation, and calculated forest biomass of the BRW. The correlation coefficient (r^2) of the regression equation is 0.60, with a probability of significance < 0.001. Continued monitoring of stream runoff at the same site, precipitation, and forest biomass both before and after planned thinning in the BRW will provide more direct quantification to the water yield change resulting from the practice. In addition, such monitoring can provide more data to refine and potentially improve the statistics of the equation, improving the confidence in the values predicted by the equation for future water yield changes from thinning or other forest biomass oriented management practices. More importantly, such continuous monitoring will provide crucial information on how potential biomass rebounding affects water yield from the watershed after the proposed thinning operation.

To fully understand the site specificity and scalability of Equation 1, it would be necessary to conduct continuous hydrologic monitoring at a site close to the treatment area drainage outlet. Depending on the location of the treatment area, such monitoring may require the development of a different monitoring station from the current one near Banchengzi Reservoir.

---

[13] Yang, X. (2013), Prediction of Temporal and Spatial Land Use Changes with a Geographic Information Database in the Miyun Reservoir Watershed, presentation at the Katoomba XVIII: Forests, Water, and People, Beijing, China.

[14] Robles, M. D., R. M. Marshall1, F. O'Donnell, E. B. Smith, J. A. Haney, D. F. Gori, 2014, Effects of Climate Variability and Accelerated Forest Thinning on Watershed-Scale Runoff in Southwestern USA Ponderosa Pine Forests, PLoS ONE 9(10): e111092, doi:10.1371/journal.pone.0111092

Attachment A

Example Calculations

Forest Thinning Calculation Example

The following example illustrates the calculation approach for the forest thinning-surface runoff equation. Input values in the example reflect local information in the Banchengzi Reservoir Watershed (BRW) where Equation 1 was developed. When local data were not available, assumptions were made and documented along with associated data gaps. The biomass reduction used in this example is taken from previous thinning operations in Huayuancun area, approximately 40 km east of the Banchenzi Reservoir in Miyun County, Beijing (Miyun County Forestry Department and Beijing Forestry Survey and Design Institute, 2008). Thinning conducted in this region between 2008 and 2009 reduced forest coverage by 189.9 m^3, roughly 10.7 percent of total growing wood stock. These example calculations assume the percent reduction of wood stock is equivalent to the percent reduction of forest biomass. Cost information is then applied to estimated yields to forecast a unit cost based on $US\$/m^{3.} yr^{-1}$.

Equation:	***q* = -0.006 × *w* + 0.3013 (n=19, r^2=0.60, p<0.001) (Zhao, 2014)**
Input:	Forest biomass (*w*) in ton/ha
Assumption:	Equation, developed for the Banchengzi Reservoir Watershed (BRW) is applicable to other places with similar geophysical and biological settings.
Calculate Baseline Surface Runoff Coefficient (Pre-Thinning):	
Equation:	*q*o = -0.006 × *w* + 0.3013
Input:	Forest biomass (*w*): 38.76 ton/ha (average 1989-2011, BRW)
Calculations:	*q*o = -0.006 × 38.76 + 0.3013 = **0.06874**
Assumption:	Unit area forest biomass for the target project area for forest thinning is the same as BRW.
Data Gap:	Unit area forest biomass for the target project area for forest thinning.
Calculate Runoff Depth (Pre-Thinning):	
Equation:	*Q*o= *q*o × annual precipitation (mm/yr)
Inputs:	Surface runoff coefficient as calculated, average annual precipitation.
Calculations:	*Q*o = 0.06874 × 623 = **42.8 mm/yr**
Assumptions:	Target project area for forest thinning has a similar annual precipitation as BRW.
Data Gap:	Annual precipitation in the target project area for forest thinning.
Calculate Baseline Surface Runoff Coefficient (Post-Thinning):	
Equation:	*q*o = -0.006 × *w* + 0.3013
Inputs:	Biomass (*w*): 38.76 × (1-10.7%) = 34.61 t/ha
Calculations:	*q*o = -0.006 × 34.61 + 0.3013 = **0.09363**
Assumptions:	A 10.7% reduction in growing wood stock reduction resulting from thinning is equivalent to a 10.7% reduction in forest biomass.
Data Gap:	Actual forest biomass reduction calculated using the same method as Zhao (2014) when the forest thinning-surface runoff equation was developed.
Calculate Runoff Depth (Post-Thinning):	
Equation:	*Q*o = *q*o × annual precipitation (mm/yr)
Inputs:	Surface runoff coefficient
Calculations:	*Q*o = 0.09363 × 623 = **58.3 mm/yr**
Assumptions:	Average precipitation constant during intervention
Data Gap:	Nearby or regional precipitation monitoring

Calculate Surface Runoff Volume Change due to Forest Thinning:	
Equation:	$\Delta V = \Delta Q \times A \times$ Conversion factor
Inputs:	Change of runoff depth due to forest thinning (ΔQ in mm/yr: 58.3 -42.8 = **15.5 mm/yr**) Area of forest thinning operation (A in ha)[9] Conversion factor: 10
Calculations:	ΔV = 15.5 × 52.89 × 10 = **8,199 m^3/yr**
Data Gap:	Area of forest thinning operation
Calculate Cost of Increased Runoff Volume due to Forest Thinning:	
Equation:	Total Cost: Area × Unit area cost Unit cost: Total Cost (US$) / Increased Water Volume = Cost per water volume (US$/m3)
Inputs:	Area of forest thinning operation (ha) Average unit area cost (US$/ha)[15] Increased water volume (m3)
Calculations:	Total cost: 52.89 ha × $211.87/ha = $11,205 Unit cost: $11,205 ÷ 8,199 m3/yr = **$1.37/$m^3 \cdot yr^{-1}$**
Assumptions:	Unit area cost of forest thinning is similar to that of "close-to-nature" forest management. Average unit area cost applies to all forest types with various tree species.
Data Gap:	Actual cost of forest thinning operation in project area.
Note:	Cost considerations are explored further in a separate Kieser & Associates, LLC cost curve memo.

References:

Miyun County Forestry Department and Beijing Forestry Survey and Design Institute, 2008, Forest Management Plan (2008-2017) in Huayuannangou, Xinchengzi, Miyuan County, Beijing, March, 2008.

Zhao, Yang, 2014, Runoff Evolution of Small Basins in the Miyun Reservoir Watershed under Changing Environment (PhD dissertation), Chapter 7, Beijing Forestry University, 2014.

[15] Values taken from Miyun County Forestry Department and Beijing Forestry Survey and Design Institute (2008) for "close-to-nature" forest management.