



Determination of minimum flood flow for regeneration of floodplain forest from inundated forest width-stage curve

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Abstract: Floods are essential for the regeneration and growth of floodplain forests in arid and semiarid regions. However, river flows, and especially flood flows, have decreased greatly with the increase of water diversion from rivers and/or reservoir regulation, resulting in severe deterioration of floodplain ecosystems. Estimation of the flood stage that will inundate the floodplain forest is necessary for the forest's restoration or protection. To balance water use for economic purposes and floodplain forest protection, the inundated forest width method is proposed for estimating the minimum flood stage for floodplain forests from the inundated forest width-stage curve. The minimum flood stage is defined as the breakpoint of the inundated forest width-stage curve, and is determined directly or analytically from the curve. For the analytical approach, the problem under consideration is described by a multi-objective optimization model, which can be solved by the ideal point method. Then, the flood flow at the minimum flood stage (minimum flood flow), which is useful for flow regulation, can be calculated from the stage-discharge curve. In order to protect the forest in a river floodplain in a semiarid area in Xinjiang subject to reservoir regulation upstream, the proposed method was used to determine the minimum flood stage and flow for the forest. Field survey of hydrology, topography, and forest distribution was carried out at typical cross sections in the floodplain. Based on the survey results, minimum flood flows for six typical cross sections were estimated to be between 306 m³/s and 393 m³/s. Their maximum, 393 m³/s, was considered the minimum flood flow for the study river reach. This provides an appropriate flood flow for the protection of floodplain forest and can be used in the regulation of the upstream reservoir.

Key words: floodplain forest; regeneration flow; minimum flood stage; inundated forest width method; ideal point method

1 Introduction

Among various types of forest in arid and semiarid regions, the floodplain forest is an important type that forms a strip of green barrier to soil erosion and desertification. It is crucial for the protection of the local environment and the development of animal husbandry (Shang

This work was supported by the National Natural Science Foundation of China (Grant No. 50879041) and the New Century Excellent Talents in University (NCET) Program of the Ministry of Education of China (Grants No. 06-0059 and 07-0814).

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Received Apr. 14, 2010; accepted Jul. 17, 2010

et al. 2006). Floodplain forests are flood-dependent ecosystems that rely on overbank floods to provide appropriate sites for regeneration and suitable moisture conditions for seedling emergence (Hughes and Rood 2003). After establishment, floodplain forests also require adequate river stage or maintenance flows to maintain groundwater levels suitable for their normal growth. Moreover, floods may change the physical environment of the floodplain due to erosion, sedimentation, or waterlogging (Renöfält et al. 2007). Therefore, floods have significant impacts on the growth of floodplain forest and biodiversity in the floodplain zone. This study mainly focused on floods that regenerate floodplain forest, which are also called regeneration flows.

In recent decades, river flows, and especially flood flows, have decreased greatly with the rapid increase of water diversion from rivers and reservoir regulation for water supply and hydroelectric power generation. The decrease in flood flow may lead to severe deterioration of aquatic and floodplain ecosystems (Postel and Richter 2003). In order to provide for adequate water for the protection or restoration of river-related ecosystems in water resources allocation, it is necessary to calculate the environmental flows required by these ecosystems, including aquatic ecosystems and floodplain forests. In the past several decades, over 200 environmental flow methodologies have been developed in 44 countries (Tharme 2003). They can be classified as hydrological, hydraulic rating, habitat simulation, holistic, combination, and other types of methodologies. However, most of these methods concern only the protection of aquatic ecosystems.

Understanding the mechanisms of forest response to flow regime is essential to evaluating the impact of river regulation on floodplain forests (Renöfält et al. 2007; Beauchamp and Stromberg 2008). These mechanisms are not yet fully understood for different forest and river types. Several methods of estimating the flow necessary for the protection of floodplain forests have been proposed, including spatial and temporal comparisons (Braatne et al. 2008), the recruitment box model (Mahoney and Rood 1998), and the dynamic simulation model (Ahn et al. 2007). However, these methods usually require a large amount of data that are difficult to obtain, which limit their applicability in river management practice.

The main purpose of this paper is to propose the inundated forest width method of estimating the flood flow necessary for the regeneration of floodplain forest, which is applicable in cases lacking detailed information on the relationship between forests and floods. This method was applied to a river reach in a semiarid area in Northwest China.

2 Inundated forest width method for determining minimum flood stage and flow for floodplain forest

2.1 Inundated forest width method

The regeneration of floodplain forests relies heavily on floods. The area of the inundated floodplain provides the possibility of seedling emergence. To protect the floodplain forests, the

inundated floodplain area should be as large as possible. However, the peak flood flow usually decreases significantly in response to reservoir regulation, and it is usually impossible to inundate the whole floodplain forest during a flood event.

In general, the area of an inundated floodplain forest increases with the flood stage. However, the estimation of inundated forest area during a flood event is difficult due to the complexity of overbank flood evolution, which is influenced by topography and forest distribution. With the environmental flow evaluation transect approach, the inundated forest width at typical cross sections can be used as an index for the renewable forest habitat. As an analogue to the wetted perimeter method (Annear and Conder 1984; Gippel and Stewardson 1998) for determining the minimum environmental flow for the protection of aquatic ecosystems, the inundated forest width method was developed to estimate the minimum flood stage and flow necessary for the regeneration of floodplain forest. Major differences between these two methods are described in Table 1.

Table 1 Comparison of wetted perimeter method with inundated forest width method

Method	Protection goal	Habitat index	Flow index	Result
Wetted perimeter method	Aquatic ecosystem	Wetted perimeter	Discharge	Minimum environmental flow
Inundated forest width method	Floodplain forest	Inundated forest width	Stage	Minimum flood stage

As opposed to the wetted perimeter method based on the wetted perimeter-discharge curve, in the inundated forest width method the wetted perimeter is replaced by the inundated forest width, and discharge is replaced by flood stage. The inundated forest width represents the habitat of floodplain forest across a stream cross section, which is restricted to the part of the cross section suitable for forest growth and inundated by the flood at a specified flood stage. This is appropriate since floods are essential to the regeneration of floodplain forests in arid and semiarid regions, and forests grow only in suitable geological and topographical conditions.

There are several reasons to use the river and floodplain stage rather than river discharge. First, the physical and ecological conditions for the regeneration of floodplain forest are mainly determined by the floodplain stage rather than the amount of water (Mahoney and Rood 1998). Second, the stage is more comparable to discharge for different stream sizes (Hughes and Rood 2003). Third, measurement or calculation of discharge for overbank floods is difficult. Therefore, the stage is a simple and appropriate index to describe the river flood.

The inundated forest width varies with the flood stage. For a specified geometry and forest distribution of a cross section, the inundated forest width may change rapidly over a certain range of stream stage, and this range is favorable to providing more renewable forest habitat for a small increase of stage. It can also change slowly across other ranges of stream stage, where the increase of stage provides a small increase of renewable forest habitat. Therefore, there may exist a critical stage at which the inundated forest width changes moderately. Similar to the widely used wetted perimeter method for determining minimum

environmental flows for aquatic ecosystems, this critical stage corresponds to the breakpoint of the inundated forest width-stage curve (Fig. 1), and can be defined as the minimum flood stage for forest regeneration at the cross section. Below this critical stage, the inundated forest width decreases rapidly, which is unfavorable for the regeneration of floodplain forest. Therefore, the present method is comparable to the wetted perimeter method.

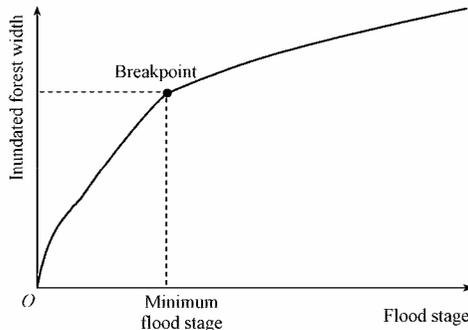


Fig. 1 Illustration of inundated forest width-stage curve

2.2 Determination of minimum flood stage from inundated forest width-stage curve

The inundated forest width-stage curve is the base for obtaining the minimum flood stage for forest protection using the inundated forest width method. To obtain the inundated forest width-stage curve, field survey of hydrology, topography, and forest distribution at typical cross sections of the floodplain is necessary. The results of the topographical survey can be used to determine the inundation scope at different flood stages. Considering the forest distribution, the inundated forest width at different flood stages can be described as $F(H)$, where F is the inundated forest width (m) and H is the flood stage (m).

Once the relationship between inundated forest width and flood stage is obtained, it can be further used to determine the minimum flood stage for the floodplain forest using the inundated forest width method. If there exists an obvious breakpoint in the inundated forest width-stage curve, the minimum flood stage can be determined directly from the curve, which is simple and straightforward. Similar to the wetted perimeter method, the determination of the breakpoint in a curve is usually subjective and highly dependent on the scale.

To eliminate the scaling effect, dimensionless stage and forest width are used instead. From the results of field survey of hydrology and forest distribution, the maximum width of the forest (m) that can be inundated by the flood, F_{\max} , can be obtained. Supposing the stage corresponding to F_{\max} is H_{\max} , dimensionless stage and forest width can be defined as

$$h = \frac{H - H_0}{H_{\max} - H_0} \quad (1)$$

$$f(h) = \frac{F(H)}{F_{\max}} \quad (2)$$

where h and $f(h)$ are dimensionless flood stage and inundated forest width, respectively, and H_0 is the minimum flood stage (m) that can inundate the floodplain forest at the study cross section. When using Eqs. (1) and (2), both flood stage and inundated forest width range between 0 and 1.

To overcome the subjectivity of determining the breakpoint of the wetted perimeter-discharge curve visually, Gippel and Stewardson (1998) proposed defining the breakpoint as the place where the slope of the curve equals a critical value (usually 1) or where the curvature of the curve is maximized. These two methods were called the slope method and the curvature method, respectively. Shang (2008) proposed a multiple-criteria decision-making approach to estimating minimum environmental flow from the wetted perimeter-discharge curve, and solved the multi-objective optimization model with the ideal point method. After theoretical and practical analysis of the slope method, the curvature method, and the ideal point method, Shang (2008) found that the slope method and the ideal point method based on Hamming distance give the same results of minimum environmental flow and are appropriate to defining the minimum environmental flow from the wetted perimeter-discharge curve. Similarly, we used the ideal point method based on Hamming distance to determine the minimum flood stage from the inundated forest width-stage curve.

The multi-objective optimization model for balancing water use for economic purposes and floodplain forest protection can be written as

$$\begin{cases} \min z_1 = h \\ \max z_2 = f(h) \\ 0 \leq h \leq 1 \end{cases} \quad (3)$$

Eq. (3) has two contradictory objectives, z_1 and z_2 . The first objective is to minimize the flood stage, which is equivalent to maximum water diversion from rivers for economic development. The second objective is to maximize the inundated forest width so as to protect the floodplain forest. For such types of multi-objective optimization models, usually only efficient solutions or Pareto optimal solutions can be obtained using various algorithms for multi-objective programming, of which the ideal point method is an effective one. The ideal point is a supposed point in the objective space whose components are the optimal values of each single objective. For Eq. (3), the ideal point is (0, 1), which represents a supposed situation with minimum flood stage (or maximum water use for economic purposes) and maximum inundated forest width. In the ideal point method, possible options are ranked in terms of their distances to the ideal point. Options closest to the ideal point can be considered Pareto optimal solutions of the multi-objective optimization model. For Eq. (3), the minimum flood stage can be obtained from the point closest to the ideal point by Hamming distance (d), which is

$$\min d(h) = w_1 h + w_2 [1 - f(h)] \quad (4)$$

where w_1 and w_2 are non-negative weights and $w_1 + w_2 = 1$. If water use for economic

purposes and floodplain forest protection are equally important, i.e., $w_1 = w_2$, Eq. (4) can be rewritten as

$$\min d(H) = \frac{1}{2} \left[1 + \frac{H - H_0}{H_{\max} - H_0} - \frac{F(H)}{F_{\max}} \right] \quad (5)$$

The optimal flood stage can be obtained from the minimization of d in Eq. (5).

2.3 Determination of minimum flood flow

River flow is more important in reservoir regulation and water resources allocation. The minimum flood flow corresponding to the optimal flood stage can be determined from the discharge-stage curve. The relationship between discharge and stage is mainly related with the geometry of the channel, and can be established by flow measurements at different stages, or calculation with Manning's or Chezy's equation (Brunner 2002). In this study, the discharge-stage curve was obtained from flow measurements at different stages.

3 Study area and field survey

3.1 Study river reach

This study focused on the middle reach of a river in a semiarid area in Xinjiang, in Northwest China. This reach is about 90 km long and the river flows from east to west between two mountains. River runoff is mainly recharged by glacier and snow melt, rainfall, and groundwater. The drainage area upstream is about 6 000 km². Based on historical hydrological records from 1958 to 2004, the mean annual flow is about 117 m³/s, and the annual runoff shows little variation because the coefficient of variation is only 0.18. However, natural runoff varies greatly within a year (Fig. 2). The proportions of natural runoff in winter (December to February) and summer (June to August) to annual natural runoff are approximately 10% and 55%, respectively. This braided river reach has one main channel and several branch channels. The small tributaries, whose discharges are very small compared with the main stream, flow into the main stream from the right bank (Fig. 3).

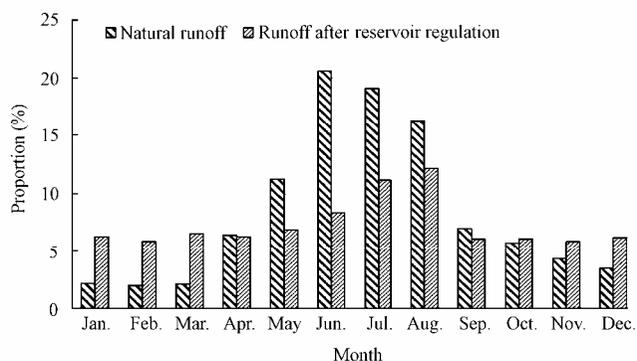


Fig. 2 Comparison of proportions of monthly runoff to annual runoff for natural runoff and runoff after reservoir regulation

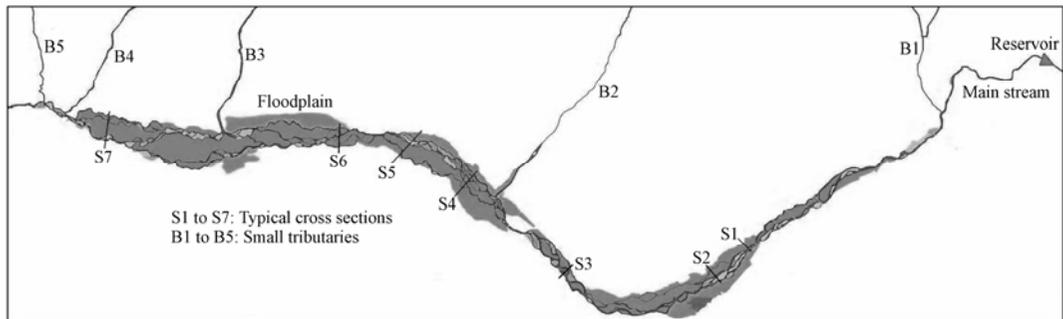


Fig. 3 Sketch of study river reach, floodplain (shaded area), and surveyed cross sections

To develop hydroelectric power and to supply water for agriculture and industry, a reservoir has been built at the outlet upstream. With the regulation of the upstream reservoir and water diversion, the annual runoff has decreased, and the seasonal variation of runoff has become less pronounced (Fig. 2). Discharge in the flood season has dropped significantly. These changes may have a great impact on floodplain forest in the middle reach (Fig. 3) that relies on floods for regeneration.

3.2 Floodplain forest

Floodplain forest along the river is important for both local development and environmental protection, and is the major concern of this study. The floodplain lies in a semiarid area, with mean annual precipitation of 360 mm to 400 mm and mean annual evaporation from the evaporation pan (with a diameter of 20 cm) of 1 360 mm to 1 710 mm. The width of the floodplain varies from less than 100 m to about 1 500 m, and the total area is about 73 km² (Fig. 3).

With water recharge from the river and mountains, the floodplain provides suitable moisture conditions for the growth of trees. It is a deciduous broadleaf forest with the dense-leaf poplar (*Populus talassica*) being the constructive species. The dense-leaf poplar is a kind of deciduous broadleaf tree that mainly grows in western Xinjiang and Central Asian countries. It grows primarily in river valleys in mountain areas and piedmont plains. The floodplain under consideration is one of main areas where the dense-leaf poplar grows in Xinjiang, China. The seed dispersal and seedling emergence of trees are closely related with flooding. Flooding is therefore the driving force for the regeneration of the dense-leaf poplar and other trees in the study floodplain.

In some parts of the floodplain, the forest has deteriorated to shrubbery mainly composed of sea-buckthorn (*Hippophae rhamnoides*) due to the change of the main river course or artificial disturbance.

Remote sensing data and field survey show that the area of the floodplain forest is about 45.5 km².

3.3 Field survey of topography and forest distribution at typical cross sections

To prevent the floodplain forest from further degradation due to flow regulation, the appropriate flood stage is required to inundate the floodplain in the seedling stage, usually in May. Considering the tradeoff between water use for economic purposes and floodplain forest protection, we used the inundated forest width method to determine the minimum flood flow for the floodplain forest.

Considering the topography, floodplain forest distribution, and accessibility of the survey site, we chose seven typical cross sections, S1 to S7 (Fig. 3), to estimate the minimum flood stage and flow. Topography, forest distribution, historical flood stage, and discharge-stage relationship at these cross sections were surveyed by the local Hydrology and Water Resources Survey Bureau from August 2006 to July 2007.

4 Results and discussion

Field survey shows that trees at cross section S4 mainly grow in places higher than the highest flood stage. This indicates that they are less influenced by the flood and therefore this cross section was excluded from further analysis. The other six sections were used to determine the minimum flood stage and flow for the floodplain forest. In the following analysis, ground elevation and river stage are relative elevation or relative stage to a selected point for each cross section. The floodplain forest distribution at typical cross sections is given in Table 2.

Table 2 Summary of floodplain forest distribution at typical cross sections

Section	Number of forest segment	Range of forest segment (m)	Width (m)	Total width (m)	Range of relative elevation (m)
S1	3	7-51	44	471	8.86-9.01
		84-176	92		7.69-9.05
		458-793	335		9.93-10.33
S2	3	26-184	158	594	35.51-35.64
		289-437	148		33.89-34.31
		665-953	288		32.74-33.06
S3	2	76.4-93.4	17	166	37.50-38.46
		180-329	149		37.82-38.13
S5	2	322-420	98	745	36.17-36.98
		824-1471	647		36.39-36.50
S6	2	607-727	120	128	19.58-19.98
		1165-1173	8		17.86-18.36
S7	1	18-1150	1132	1132	14.10-15.30

4.1 Minimum flood stage and flow for cross section S1

The survey of topography and forest distribution at cross section S1 (Fig. 4(a)) shows that

there are several branches across this section. Forest mainly grows on the right side of the floodplain, and the total width of the forest is about 471 m. The forest width below the highest flood stage (9.14 m) at this section is 326 m, which was the major concern in the analysis. The calculated inundated forest width-stage curve in Fig. 4(b) shows that there is an obvious breakpoint in the curve at a stage of 8.45 m. At this stage, the inundated forest width is about 154 m, about 47% of the floodplain forest width. Above this stage, the inundated forest width increases slowly until the stage reaches 8.85 m, and then increases rapidly. Moreover, the minimum value of Hamming distance in Eq. (5) accords with the above breakpoint. This breakpoint of the inundated forest width-stage curve can be considered the minimum flood stage for section S1, and the corresponding minimum flood flow is 306 m³/s.

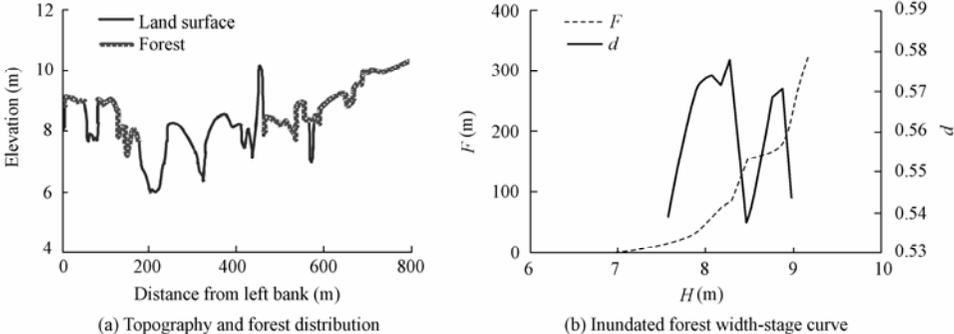


Fig. 4 Determination of minimum flood stage for cross section S1

4.2 Minimum flood stage and flow for cross section S2

Fig. 5 shows the topography and forest distribution at cross section S2 and the estimated inundated forest width-stage curve. As shown in Fig 5(a), the forest along this section can be divided into three parts, and the total width is 594 m. However, only the middle (from 289 m to 437 m) and left (from 665 m to 953 m) parts are affected by flooding, which is considered below.

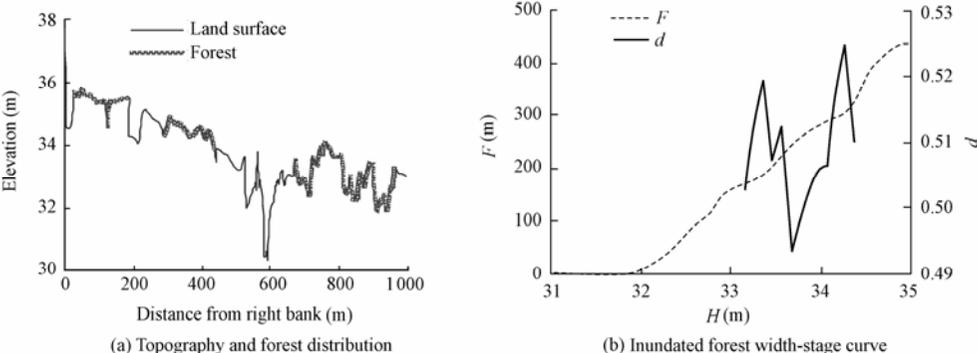


Fig. 5 Determination of minimum flood stage for cross section S2

There is no obvious breakpoint in the inundated forest width-stage curve. In this case, the minimum flood stage can be determined using Eq. (5). The maximum inundated forest width

here is $F_{\max} = 436$ m. Based on Eq. (5), the minimum Hamming distance occurs at a flood stage of 33.66 m (Fig. 5(b)), and the corresponding minimum flood flow is $383 \text{ m}^3/\text{s}$. At this flood stage, 57% of the forest is inundated.

4.3 Summary of minimum flood flows for all cross sections

The minimum flood stages and flows for the other cross sections were calculated in a manner similar to the process described above. Table 3 is a summary of the results. The minimum flood flows for different cross sections varied from $306 \text{ m}^3/\text{s}$ at S1 to $393 \text{ m}^3/\text{s}$ at S5. To protect the floodplain forest, the maximum of these values, $Q_m = 393 \text{ m}^3/\text{s}$, is considered the minimum flood flow for the study river reach. Indexes for different cross sections corresponding to Q_m are given in Table 4.

Table 3 Summary of minimum flood stages and flows for typical cross sections

Cross section	Total forest width (m)	Maximum flood stage (m)	Forest width below highest flood stage (m)	Minimum flood stage (m)	Inundated forest width (m)	Proportion of inundated forest (%)	Minimum flood flow (m^3/s)
S1	471	9.14	326	8.45	154	47	306
S2	594	35.05	436	33.66	250	57	383
S3	166	40.02	166	38.27	161	97	330
S5	745	37.97	745	36.98	455	61	393
S6	128	21.53	128	20.32	124	97	372
S7	1 132	16.88	1 132	15.36	1 109	98	346

Table 4 Flood stages and inundated forest widths for typical cross sections when $Q_m = 393 \text{ m}^3/\text{s}$

Cross section	Flood stage (m)	Inundated forest width (m)	Proportion of inundated forest (%)
S1	8.62	162	50
S2	33.69	253	58
S3	38.50	166	100
S5	36.98	455	61
S6	20.40	128	100
S7	15.49	1 132	100

When the discharge increased to Q_m from the minimum flood flow for a specified cross section, the increments of flow were much greater than that of the inundated forest width. For example, they were 28% and 5%, respectively, for section S1. This indicates that the minimum flood stage determined with the ideal point method is appropriate, since the increase of inundated forest width is very small when the stage is higher than the minimum flood stage.

When the flood discharge reached Q_m , the area of inundated forest was estimated from forest distribution and the proportion of inundated forest at each cross section, which was about 36.2 km^2 or about 80% of the total forest area. The forest along three sections (S3, S6, and S7) was entirely inundated. Considering the dense distribution of floodplain forest between sections S6 and S7, the determined minimum flood flow can provide favorable

conditions for the regeneration of forest in the study river reach.

5 Conclusions

Floods provide the possibility for the regeneration of floodplain forests in arid and semiarid regions. The inundated forest width method is proposed to estimate the minimum flood stage for floodplain forest from the inundated forest width-stage curve. The minimum flood stage is defined as the breakpoint of the inundated forest width-stage curve, and can be determined directly or analytically from the curve using the ideal point method for multi-objective optimization. Flood flow corresponding to the minimum flood stage can be used as an index for floodplain forest protection in reservoir regulation and water resources allocation.

To protect the floodplain forest subjected to reduced flooding caused by reservoir regulation and water diversion in a semiarid area in Northwest China, the proposed method was used to determine the minimum flood stage and corresponding flood flow. The maximum value of the minimum flood flows for six typical cross sections, 393 m³/s, was considered the minimum flood flow for the study river reach. For this flood flow, about 80% of the forest is inundated along the study river reach. The results indicate that the proposed method is appropriate for determining the minimum flood flow for the protection of floodplain forest. This method is applicable to floodplain forests that rely on flood flow for regeneration where there is a need to balance water use for economic purposes and floodplain forest protection.

In the inundated forest width method, the inundated forest width is considered the index for the normal regeneration of floodplain forest, and the relation between flood and forest is not fully considered. In future studies, the response of floodplain forest to river flow should be investigated.

References

- Ahn, C., Moser, K. F., Sparks, R. E., and White, D. C. 2007. Developing a dynamic model to predict the recruitment and early survival of black willow (*Salix nigra*) in response to different hydrologic conditions. *Ecological Modelling*, 204(3-4), 315-325. [doi:10.1016/j.ecolmodel.2007.01.006]
- Annear, T. C., and Conder, A. L. 1984. Relative bias of several fisheries instream flow methods. *North American Journal of Fisheries Management*, 4(4b), 531-539. [doi:10.1577/1548-8659(1984)4<531:RB OSFI>2.0.CO;2]
- Beauchamp, V. B., and Stromberg, J. C. 2008. Changes to herbaceous plant communities on a regulated desert river. *River Research and Applications*, 24(6), 754-770. [doi:10.1002/tra.1078]
- Braatne, J. H., Rood, S. B., Goater, L. A., and Blair, C. L. 2008. Analyzing the impacts of dams on riparian ecosystems: A review of research strategies and their relevance to the Snake River through Hells Canyon. *Environmental Management*, 41(2), 267-281. [doi:10.1007/s00267-007-9048-4]
- Brunner, G. W. 2002. *HEC-RAS River Analysis System Hydraulic Reference Manual (Version 3.1)*. Davis: U. S. Army Corps of Engineers.
- Gippel, C. J., and Stewardson, M. J. 1998. Use of wetted perimeter in defining minimum environmental flows. *Regulated Rivers: Research and Management*, 14, 53-67.
- Hughes, F. M. R., and Rood, S. B. 2003. Allocation of river flows for restoration of floodplain forest ecosystems: A review of approaches and their applicability in Europe. *Environmental Management*, 32(1),

12-33. [doi:10.1007/s00267-003-2834-8]

- Mahoney, J. M., and Rood, S. B. 1998. Streamflow requirements for cottonwood seedling recruitment: An integrative model. *Wetlands*, 18(4), 634-645. [doi:10.1007/BF03161678]
- Postel, S., and Richter, B. 2003. *Rivers for Life: Managing Water for People and Nature*. Washington, D. C.: Island Press.
- Renöfält, B. M., Merritt, D. M., and Nilsson, C. 2007. Connecting variation in vegetation and stream flow: The role of geomorphic context in vegetation response to large floods along boreal rivers. *Journal of Applied Ecology*, 44(1), 147-157. [doi:10.1111/j.1365-2664.2006.01223.x]
- Shang, S. H., Hu, Q. F., Lei, Z. D., and Yang, S. X. 2006. Ecological water use of forest-meadow land in a river valley in Xinjiang. *Proceedings of the International Symposium on Sustainable Water Resources Management and Oasis-Hydrosphere-Desert Interaction in Arid Regions*, 452-456. Beijing: Tsinghua University Press. (in Chinese)
- Shang, S. H. 2008. A multiple criteria decision-making approach to estimate minimum environmental flows based on wetted perimeter. *River Research and Applications*, 24(1), 54-67. [doi:10.1002/rra.1047]
- Tharme, R. E. 2003. A global perspective on environmental flow assessment: Emerging trends in the development and application of environmental flow methodologies for rivers. *River Research and Applications*, 19(5-6), 397-441. [doi:10.1002/rra.736]