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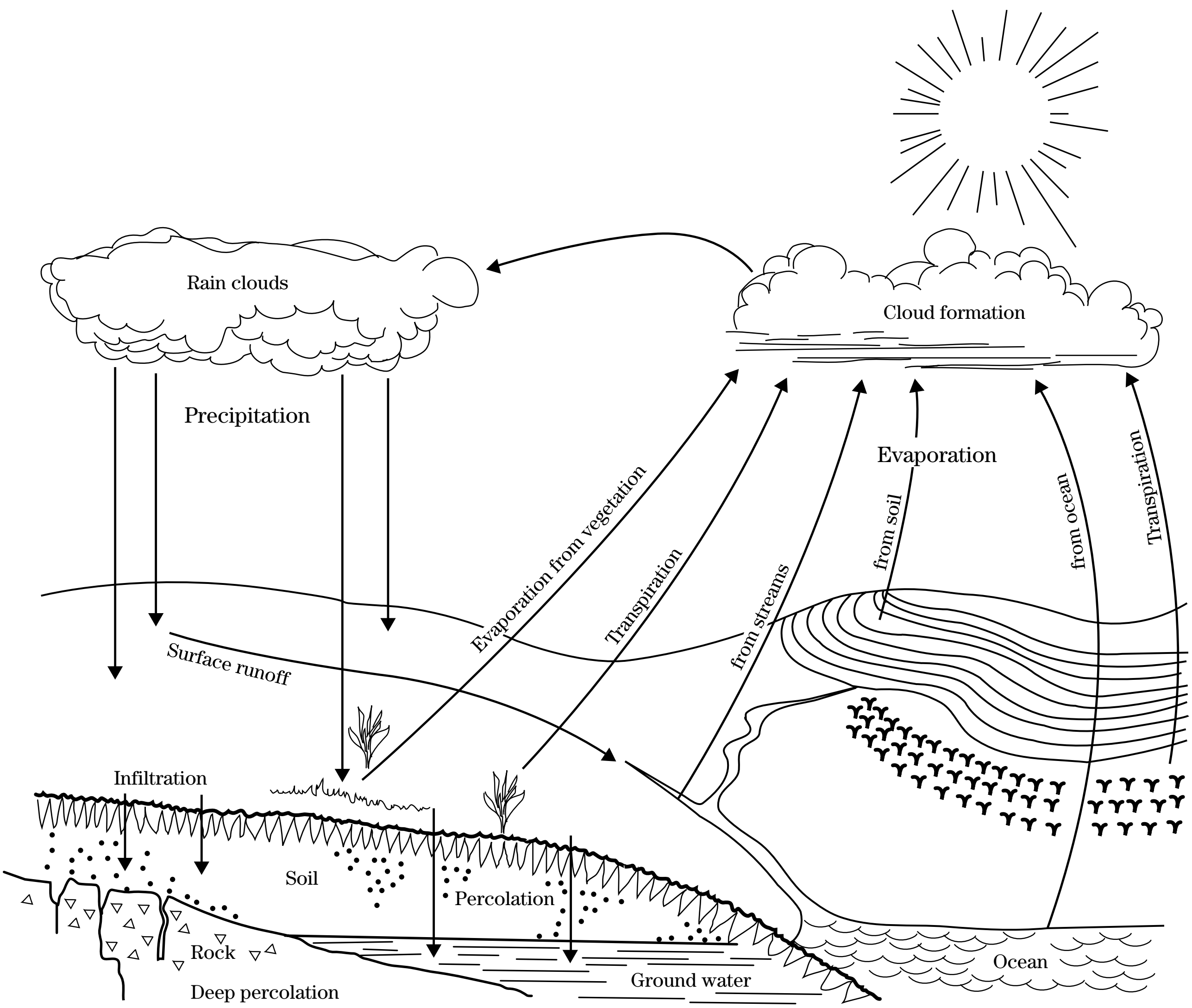
Part 630 Hydrology
National Engineering Handbook

Chapter 13 Stage Inundation Relations



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Chapter 13 was originally prepared by **Victor Mockus** (retired) in 1956 and was reprinted with minor revisions in 1971. This version was revised by **William Merkel**, hydraulic engineer, Natural Resources Conservation Service (NRCS), Beltsville, Maryland, and **Helen Fox Moody**, hydraulic engineer, NRCS, Beltsville, Maryland, under the guidance of **Donald E. Woodward**, retired, NRCS, Washington, DC.

Chapter 13 Stage Inundation Relations

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630.1300 Introduction

Water resources planning often requires tabular or plotted data showing the relation between the area inundated and stream stage, discharge, flood volume, or frequency. These types of data are called stage inundation relations and are often used in the economic evaluation of a project's justification. The information is developed using data obtained in project field surveys. Different planning efforts require different levels of accuracy and detail in stage inundation relations, and the expected use of the information should ultimately dictate the preferred analysis technique. Section 611.0201 of the National Water Resources Economics Handbook provides some guidance for flood damage analysis.

630.1301 Stage versus area inundated methods

(a) Simple cases

This method relates the acres flooded in a stream reach to the stage somewhere along the length of the reach, generally at the downstream end. The stage inundation relation shows the number of acres flooded at different depths appropriate for the particular analysis. The simplest case occurs when one cross section is used to represent conditions in a reach. Table 13–1 shows a typical computation of a stage versus total area inundated relation for this case.

The acres inundated at selected depths of flooding are computed as shown in table 13–2 and figure 13–1 (a–e). Figure 13–2 shows how the results are generally presented.

Table 13–1 Sample computation of stage versus area inundated for a simple case using a representative cross section in the reach

Stage (ft) (1)	Cross section top width (ft) (2)	Width minus channel width (ft) (3)	Inundated area in reach 1/ (acres) (4)
4 2/	24	0	0
6	92	68	13.5
8	367	343	68.0
10	608	584	115.8
12	786	762	151.1
14	872	848	168.2

1/ Computed using the width minus channel width (col. 3) and the valley length of the reach. In this case, the reach is 8,640 feet long. To get acres, the formula is:

$$\frac{8,640}{43,560}\ (\text{col. } 3) = 0.1984\ (\text{col. } 3) = \text{col. } 4$$

2/ Stage at which flood damages begin is 4 feet.

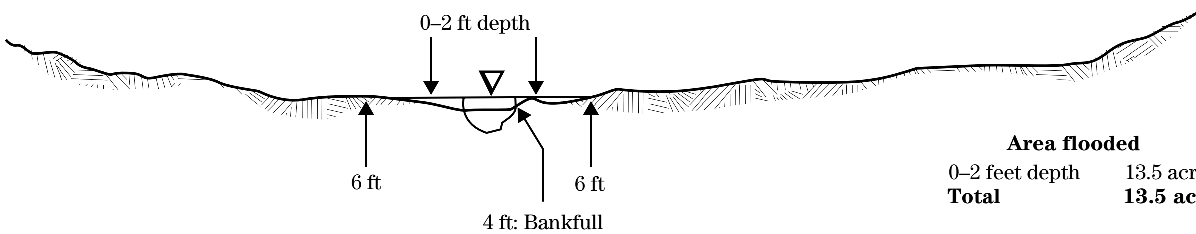
Table 13–2 Sample computation of stage versus area inundated at selected depths of flooding

Stage (ft) (1)	Total area inundated (acres) (2)	Acres inundated at given depths 1/			
		0–2 (ft) (3)	2–4 (ft) (4)	4–6 (ft) (5)	>6 2/ (ft) (6)
4	0	0	0	0	0
6	13.5	13.5	0	0	0
8	68.0	54.5	13.5	0	0
10	115.8	47.8	54.5	13.5	0
12	151.1	35.3	47.8	54.5	13.5
14	168.2	17.1	35.3	47.8	68.0

1/ Values can also be obtained graphically. See figure 13–2.
2/ Values are those of the total area inundated (col. 2) shifted downward three lines.

Figure 13–1 Increasing area flooded caused by increasing flooding stage

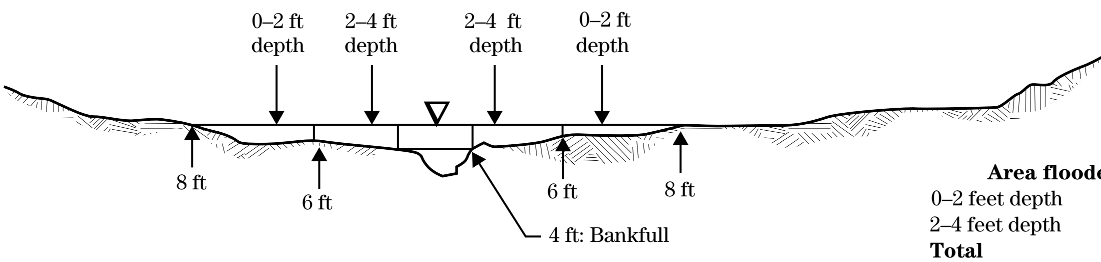
(a) 6-ft stage



Area flooded

0–2 feet depth	13.5 acres
Total	**13.5 acres**

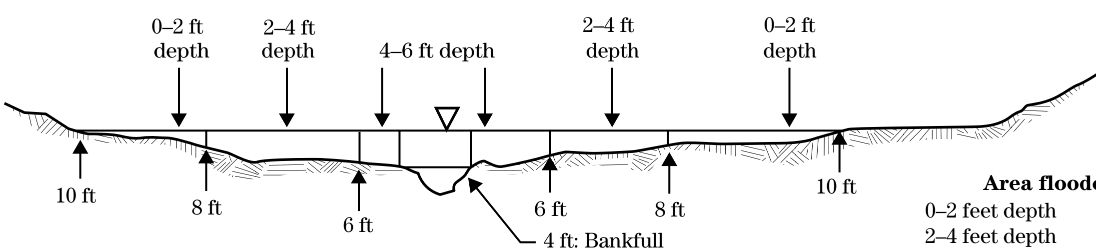
(b) 8-ft stage



Area flooded

0–2 feet depth	54.5 acres
2–4 feet depth	13.5 acres
Total	**68.0 acres**

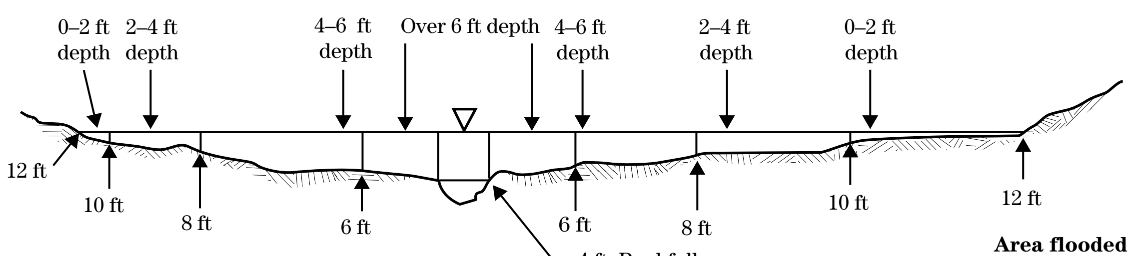
(c) 10-ft stage



Area flooded

0–2 feet depth	47.8 acres
2–4 feet depth	54.5 acres
4–6 feet depth	13.5 acres
Total	**115.8 acres**

(d) 12-ft stage

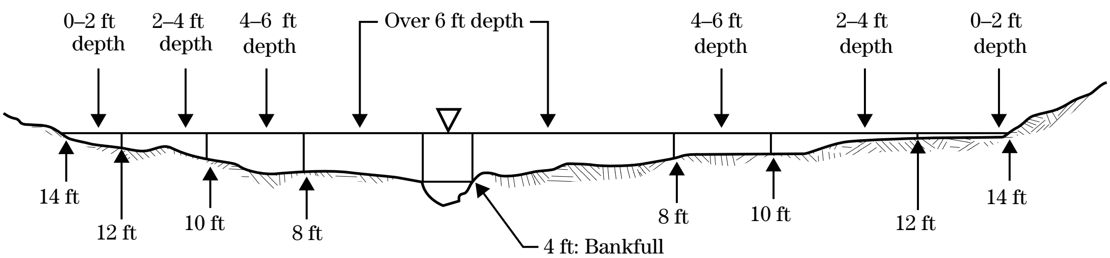


Area flooded

0–2 feet depth	35.3 acres
2–4 feet depth	47.8 acres
4–6 feet depth	54.5 acres
Over 6 feet depth	13.5 acres
Total	**151.1 acres**

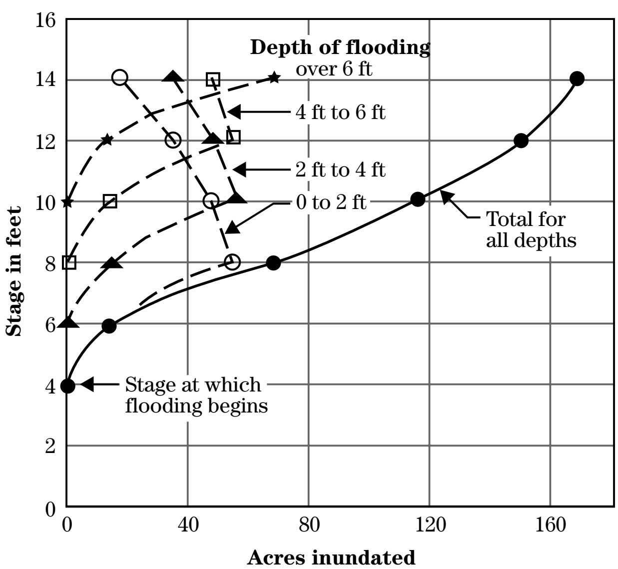
Figure 13–1 Increasing area flooded caused by increasing flooding stage—Continued

(e) 14-ft stage



Area flooded	
0–2 feet depth	17.1 acres
2–4 feet depth	35.3 acres
4–6 feet depth	47.8 acres
Over 6 feet depth	68.0 acres
Total	**168.2 acres**

Figure 13–2 Area flooded at given depth of flooding increments



(b) Complex cases

The computation of the stage inundation relation becomes more complex when more than one cross section per reach is used, and also if a variable length of reach is used. The number of acres flooded at various depths is sometimes obtained by comparing the areas between flow lines plotted on a map of the flood plain.

When two cross sections per reach are used and the drainage areas at the sections are not significantly different in size, the sections may be averaged as shown in table 13–3. Determination of acres flooded for given depth increments follows the procedure of table 13–2. When the drainage areas of the two cross sections are significantly different in size, the sections may be averaged as shown in table 13–4, with the procedure of table 13–2 used to get flooding by depth increments. In this case, the inundated acreage has been related to the lower or downstream end, the foot of the reach. The footnote for table 13–3 tells how the acreage may be related to the middle of the reach. The method used in table 13–4 is probably best when acreage is related to the lower end of the reach, as shown.

In table 13–4, column 4, the corresponding discharges at the upstream cross section have been proportioned using the ratio of the bankfull discharges. This method is applicable when the channels are not excessively eroded or silted and the cross section rating curves are consistent between the two cross sections. The method of expressing the same discharge in cubic feet per second per square mile is sometimes used, but this method ignores the fact that this relation is seldom linear. The upstream bankfull discharge in cubic feet per second per square mile is normally greater (for natural channels in noncohesive materials and in an equilibrium condition or nearly so) than the downstream bankfull discharge in cubic feet per second per square mile. In these cases, discharges should be used that are of the same frequency. For example, the top width for the 2-year frequency discharge at the upper section is averaged with the top width for the 2-year frequency discharge at the lower section, and so on. When this frequency method is not used and the channel sections vary widely, much accuracy in the averaging should not be expected.

With more than two cross sections, a system of weighting must be used. Figure 13–3 shows a typical reach with seven cross sections. The weight for section A is a/L, for section B it is b/L, and so on. Table 13–5 shows a computation using three cross sections.

The method illustrated in table 13–2 is used to complete the work.

Table 13–3 Sample computation of stage versus area inundated with two cross sections in the reach (head and foot) and drainage areas not significantly different

Foot of reach cross section 1		Head of reach cross section 2		Areas related to foot of reach [1/]			
stage (ft) (1)	top width (ft) (2)	stage (ft) (3)	top width (ft) (4)	stage (ft) (5)	average top width (ft) (6)	average top width minus channel width (ft) (7)	inundated area in reach [2/] (acres) (8)
10 [3/]	41	7 [3/]	30	10 [3/]	35.5	0	0
12	168	9	125	12	146.5	111.0	10.8
14	646	11	478	14	562.0	526.5	51.1
16	1,070	13	786	16	928.0	892.5	86.7

1/ If related to middle of reach, the stages (col. 5) are 8.5, 10.5, 12.5, and 14.5

2/ Length of valley in reach is 4,230 feet, and $\frac{4,230}{43,560}$ (col. 7) = (col. 8)

3/ Bankfull stage

Table 13–4 Sample computation of stage versus area inundated with two cross sections in the reach (head and foot) and drainage areas at the sections vary significantly

Cross section A — Foot of reach (D.A.=36.0 mi²)			Cross section B — Head of reach (D.A.=24.0 mi²)		Areas related to foot of reach (cross section A)		
stage (ft) (1)	discharge (ft^3/s) (2)	top width (ft) (3)	discharge (ft) (4)	top width (ft) (5)	average top width (ft) (6)	average top width minus channel width (ft) (7)	inundated area in reach 3/ (acres) (8)
10	720 1/	41	680 1/	32	36.5	0	0
12	1,510	168	1,426 2/	141	154.5	118.0	11.1
14	3,060	646	2,890 2/	362	504.0	467.5	43.8
16	5,030	1,070	4,751 2/	858	964.0	927.5	86.9

1/ Bankfull discharge
2/ Proportioned by the bankfull discharge ratio 680/720. For example,

$$\frac{680}{720}\left(1,510\right) = 1,426 \text{ ft}^3/\text{s}$$

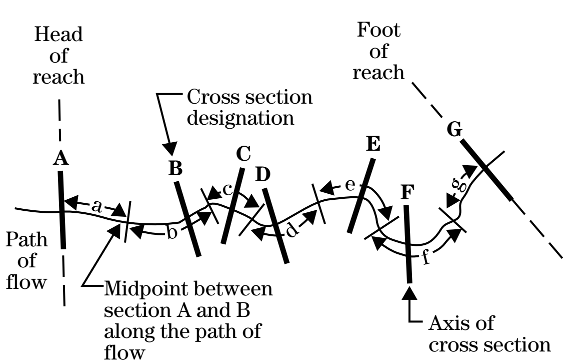
3/ Length of reach is 4,080 feet, and $\frac{4,080}{43,560}$ (col. 7) = (col. 8)

Table 13–5 Sample computation of stage versus area inundated with three cross sections in the reach and drainage areas at the sections not significantly different

Cross section 1 — weight = 0.22		Cross section 2 — weight = 0.47		Cross section 3 — weight = 0.31		Related to cross section 1		
stage (ft) (1)	top width (ft) (2)	stage (ft) (3)	top width (ft) (4)	stage (ft) (5)	top width (ft) (6)	weighted top width (ft) (7)	weighted top width minus channel width (ft) (8)	inundated area in reach 3/ (acres) (9)
8 1/	42	10 1/	44	7 1/	32	39.8 2/	0	0
10	154	12	250	9	140	194.8	155.0	30.7
12	702	14	540	11	603	595.2	555.4	109.9
14	1,100	16	832	13	948	926.9	887.1	175.5

1/ Bankfull stage. Widths at this stage are channel widths.
2/ 39.8 = 0.22 (42) + 0.47 (44) + 0.31 (32). The weights are in proportion to total reach length as shown on figure 13–3.
3/ Length of reach is 8,620 feet, and $\frac{8,620}{43,560}$ (col. 8) = (col. 9)

Figure 13–3 Flood damage reach showing weighting of area between cross sections



Lengths a, b, c, etc., are measured along the path of flow. Length of reach "L" = a+b+c+d+e+f+g. Cross section A has the weight a/L; while B has the weight b/L; and so on. Flood plain lengths may be more appropriate to use for weighting in some cases. Flood plain lengths are usually shorter than channel lengths which are illustrated here.

630.1302 Flood peak or volume versus area inundated method

This method is generally used with alluvial fan floods; although it can also be used for other types of floods instead of the stage methods described. Alluvial fan flooding occurs on the surface of an alluvial fan or similar landform on which flooding begins at an apex and is characterized by unpredictable flow paths with high flow velocities, active erosion, sediment transport, and deposition.

Step 1 Conduct field interviews for as many floods as possible to determine the extent of the areas flooded.

Step 2 Determine actual or estimated flood peak or volume for each flood, using a cross section or gage upstream from the fan as a reference point.

Step 3 Plot the flooded area, in acres, versus the flood peak or volume for each flood, using arithmetic plots to determine the relation between area and peak or volume.

Once the relation is determined, the effects of upstream projects can be computed in terms of runoff. A reduced runoff means a reduced area flooded. When a channel system within the fan is proposed for reducing flooding, hydrographs are prepared at the upstream section or gage and routed downstream.

630.1303 Frequency versus area inundated method

This method is sometimes used instead of the methods already described. It is applicable to both stream reaches and alluvial fans.

Field interviews are used to collect data on area flooded for all known floods. The earliest known flood determines the length of record, y. The techniques outlined in NEH630.18, Selected Statistical Methods, are used to perform a frequency analysis, and a frequency versus area flooded curve is developed. The area under the curve divided by y gives the average area flooded.

A major problem with this method may be that the dollar damage per acre may vary greatly from flood to flood. In such cases, a damage-frequency curve is more accurate.

630.1304 Computer determination of area inundated

(a) HEC–RAS program

Stage inundation relations may be computed using the U.S. Army Corps of Engineers' (USACE) HEC–RAS program. The USACE HEC–RAS computes acres flooded when English units are used for output. If SI (metric) units are used, the area flooded is in units of 1,000 square meters. Area flooded is computed for each profile between two cross sections based on the average top width of the flow for left overbank, channel, and right overbank segments. A total for the entire cross section is also computed.

Within HEC–RAS, the area flooded displayed for a cross section is the accumulated value from the beginning of the reach to that cross section. When the next reach is encountered, the flooded areas are reset to zero. To compute the area flooded between two cross sections, the area flooded at the downstream cross section should be subtracted from the area flooded at the upstream cross section. For more information on how to apply HEC–RAS, refer to the latest program documentation at the USACE Web site (*http://www.hec.usace.army.mil/software*).

(b) HEC–GeoRAS program

The USACE's HEC–GeoRAS program is an ArcGIS extension designed to process geospatial data for use with HEC–RAS. HEC–GeoRAS is a set of procedures, tools, and utilities for processing geospatial data with a graphical user interface (GUI). This interface allows users with limited GIS experience to build a HEC-RAS file containing geometric data from an existing digital terrain model (DTM) and complementary data sets and to process results exported from HEC–RAS, and it can be used to develop a flood inundation map based on digital elevation data.

(c) WSP2 program

Stage inundation relations may also be computed using the NRCS WSP2 program. NEH 630.31 (1993, revised 2005) describes this water surface profile program. This program is no longer actively supported by NRCS. Use of HEC–RAS for water surface profiles is recommended because of its ability to handle both subcritical and supercritical flow.

Stage inundation relations from WSP2 may be used in the ECON2 program to determine agricultural economic damages because of inundation.

Many older projects will have hydraulic data available for the WSP2 format and, if all flows are subcritical, this program may still be used. New projects should use HEC–RAS.

(d) Comparison method

In actual practice, flood plain boundaries for the return intervals being evaluated are generally drawn on a topographic map. The actual flooded area is determined and then compared to the area computed in HEC–RAS or WSP2. This comparison may be by cross section or by reach (a group of cross sections). A ratio of actual to computed flooded area is then used in a flood economics program to reflect actual flooded area more accurately.

630.1305 Combination method of determining area inundated

Additional sources of information can also be used to help define flood plains. These are geomorphic surfaces, soils, botanical, hydrologic, and historical methods. The use of these together, or of some combination, is called the combination method of flood plain delineation. The combination method has been used in various locations in the United States with good success. This method uses all the information available to define the flood plain between cross sections. Cross section locations can be better established using the combination method.

Geomorphic surfaces and features help define flood plains. An abandoned flood plain along a stream is called a terrace. A river may develop a sequence of stepped terrace levels over time as the channel cuts deeper or incises into the flood plain surface. These terraces and other features often vary with height along the channel length. Other geomorphic features typical of flood plain areas include previous river channels, oxbows, sloughs, natural levees, and backswamp deposits. Generally, the same flood along the entire watershed will flood the same feature. Often many standard flood plain features can be recognized more easily through analysis of aerial photographs than from ground inspections (Reckendorf 1968).

Soils information and maps also help to determine flood plains. It has been shown that generally the soils formed in recent depositions of alluvial materials have slight or no horizon development. Soils on terraces are generally older with more developed horizons than soils on flood plains. Thus, it is possible to use soils information and development to distinguish older or higher surfaces from younger or newer flood plains.

Botanical evidence along a stream helps identify flooding and flooding limits. Scarred tree trunks and felled trees, for instance, indicate a catastrophic event at or near their location. Sprouts growing on a fallen trunk can be dated by their tree rings. Sigafoos (1964) describes many such procedures and how this information plus a knowledge or history of past floods can help to identify flooding extent.

Hydrologic procedures use information developed from hydrologic studies, such as WinTR–20 (Computer Program for Project Formulation Hydrology) and/or HEC–RAS runs to delineate inundated areas. Gage heights can be used to relate geomorphic surfaces with historic floods.

Historic information obtained from interviews and newspaper articles can provide valuable data on extent and depth of flooding. In some cases, aerial photographs can be obtained for recent floods.

630.1306 Stereoscopic and other methods

A stereoscopic procedure can be used either to develop a stage versus area inundated relation or to check a relation developed by other methods.

Step 1 Locate the limits of a large, recent flood at each cross section on aerial photographs (4-inch to the mile preferred).

Step 2 Using a stereoscope, outline the flood plain for this flood.

Step 3 Lay out and match the photographs.

Step 4 Make a tracing of the flood plain outline. Show the cross-section locations and details of land use.

Step 5 Determine the area flooded in each reach. If stereoscopic photographs are used, the area flooded can be determined using a planimeter.

Step 6 Compute the area flooded by using the water surface width at each cross section for each reach, and multiplying by:

$$\frac{\text{reach length in feet}}{43{,}560}$$

where reach length is defined as the length of the flow path.

Step 7 Compare the area measured in step 4 with the computed area from step 5.

$$C_f = \frac{\text{measured area}}{\text{computed area}}$$

where:
C_f = correction factor

Step 8 Compute the area for various other floods using widths as in step 5 and assuming the flood plain outline increases and decreases parallel to the outline of the selected recent large flood. For a given reach length, use the correction factor of step 6, if required.

Step 9 Plot area flooded versus stage at the selected cross section.

Step 10 Determine areas flooded at required depth increments (table 13–2).

Other methods involving areal measurement are sometimes useful. For example, flood lines for each of several floods may be used to delineate inundated areas on aerial photos, which are measured and related to stage or runoff or frequency. If a flood plain delineation can be depicted on a GIS layer, its area can then be determined by GIS methods. The USACE's HEC–GeoRAS program can be used to develop a flood inundation map based on digital data. The flood boundary developed by HEC–GeoRAS can be overlaid on an aerial photograph (digital orthoquad, or DOQ) and checked for accuracy. Generally, lack of data on the location of the flood lines of historic floods limits the application of this and similar methods.

630.1307 References

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