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Engineering and Design
HYDRAULIC DESIGN FOR LOCAL FLOOD RISK MANAGEMENT PROJECTS

1. Purpose. This engineer regulation (ER) prescribes the design procedure and rationale for the hydraulic design of a local flood risk management project. Design guidance is contained in the references listed in paragraph 4 and recognized engineering texts.

2. Applicability. This regulation is applicable to all U.S. Army Corps of Engineers Headquarters (HQUSACE) elements, major subordinate commands, districts, laboratories, and field operating activities (FOA) having civil works design responsibilities.

3. Distribution Statement. Approved for public release; distribution is unlimited.

FOR THE COMMANDER:

JOHN P. LLOYD
COL, EN
Chief of Staff

*This Engineer Regulation supersedes ER 1110-2-1405 dated 30 September 1982.

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4. References.

a. 33 Code of Federal Regulations (CFR) 208.10. Local Flood Protection Works; Maintenance and Operation of Structures and Facilities. (https://www.govinfo.gov/app/collection/CFR)

b. ER 1105-2-101. Risk Assessment for Flood Risk Management Studies. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Regulations/)

c. ER 1110-1-12. Quality Management. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Regulations/)

d. ER 1165-2-21. Flood Damage Reduction Measures in Urban Areas. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Regulations/)

e. Engineer Manual (EM) 1110-2-1205. Environmental Engineering for Flood Control Channels. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

f. EM 1110-2-1413. Hydrologic Analysis of Interior Areas. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

g. EM 1110-2-1416. River Hydraulics. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

h. EM 1110-2-1418. Channel Stability Assessment for Flood Control Projects. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

i. EM 1110-2-1419. Hydrologic Engineering Requirements for Flood Damage Reduction Studies. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

j. EM 1110-2-1601. Hydraulic Design of Flood Control Channels. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

k. EM 1110-2-1619. Risk-Based Analysis for Flood Damage Reduction Studies. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

l. EM 1110-2-4000. Sedimentation Investigations of Rivers and Reservoirs. (https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/)

5. Records Management (Recordkeeping) Requirements. The records management requirement for all record numbers, associated forms, and reports required by this regulation are addressed in the Army's Records Retention Schedule—Army (RRS-A). Detailed information for all related record numbers are located in the Army Records Information Management System (ARIMS)/ RRS-A at https://www.arims.army.mil. If any record numbers, forms, and reports are not current, addressed, and/or published correctly in ARIMS/RRS-A, see the Department of the Army Pamphlet 25-403, Guide to Recordkeeping in the Army.

6. Design Rationale. The hydraulic design of a local flood risk management project must result in an efficient, reliable, resilient, and cost-effective project with appropriate consideration of life safety, environmental, and social aspects, and be consistent with the objectives defined for the flood risk management study. The hydraulic design must also fully incorporate an evaluation of hydraulic uncertainty and its impact on risk. The seven elements described below must be included in a satisfactory final design, though these elements may be only partially addressed in earlier design phases (see paragraphs 7 and 8a). Key factors to each element are identified below and should be covered in the final design.

a. Channel Efficiency. Channel cross-section, plan, and bottom profile configuration to optimize conveyance and operation and maintenance consistent with project objectives.

b. Reliability. Ability to achieve project purposes throughout project economic life; proper functioning of facilities such as pumps, gates, and trash fenders.

c. Resiliency. The ability to prepare, absorb, recover, and adapt from the effects of adversity, whether natural or man-made, under all circumstances of use.

d. Cost Effectiveness. Initial, operational, maintenance, and replacement costs optimized on an annual cost basis.

e. Environmental and Social Aspects. Sustainability, fish and wildlife, environmental and floodplain regulations, beautification, recreational opportunities, handicapped access, and mitigation of adverse impacts.

f. Risk Management. Potential safety hazards to humans and property, creation of a false sense of security, and residual risk including consequences of flows exceeding the channel capacity.

g. Uncertainty. Energy losses, cross-section geometry, survey data, computational method, and climate change.

7. Project Design Process.

a. The initial step in the hydraulic design process is to develop a hydraulic design study plan that will support the overall design study to meet all defined design objectives of the flood risk management project outlined in paragraph 6. This plan will indicate the hydraulic design studies to be performed as the design progresses through its various phases. A risk-informed consideration of the type and complexity of the hydraulic design studies required at various phases is necessary. A less complex project may require only basic hydraulic design studies, while a more complex project may require progression to more sophisticated hydraulic design studies as the overall design progresses. Regardless of complexity in the hydraulic design study or the overall study, it is imperative to fully develop all hydraulic uncertainty values for inclusion in a risk analysis of the entire project.

b. The hydraulic design study plan will identify requirements for data inputs and study results obtained from others (see Table 7.1 below) that will be necessary to properly conduct the hydraulic design studies. The hydraulic design study plan must incorporate the appropriate guidance on considering climate change; this newer element is necessary to ensure a resilient hydraulic design. Coordination with other disciplines is essential to ensure the timely availability, clear format, and technical adequacy of the hydraulic design inputs to and outputs from the hydraulic design studies. Decisions as to portions, if any, of the hydraulic design studies requiring physical or mathematical modeling by others will be noted in the plan. The plan will indicate, by calendar-based schedule or other means, the timing of hydraulic design studies, input from others, and interfacing of hydraulic design outputs with the design study.

c. Assemble initial inputs of required data/studies.

d. Conduct initial hydraulic design studies in support of the overall design study. Alternative designs must be studied and presented in sufficient detail to provide a valid basis for plan comparison and to substantiate the recommended design commensurate with the phase of the design study progress (i.e., less detail is required in early phases, and more detail in later phases).

e. Hydraulic design studies will continue, as needed, until the project construction is completed.

f. Continuous review and modification of the hydraulic design study plan in response to adjustments in the design study is essential to the hydraulic design process. This review typically is conducted at intervals but should be considered continuous overall, with requirements and concerns addressed as they arise.

Table 7.1
Typical Hydraulic Design Study Input Requirements

Hydrologic	Climate/weather (precipitation, wind, and temperature) Discharge (hydrographs, frequency, stage, and duration—annual and seasonal) Sediment (yield and flow bulking) Tides Coincident flooding Uncertainty (precipitation, runoff, measurements, etc.)
Hydraulic	Velocity Debris Ice (formation, breakup, etc.) Slope Energy losses (roughness, transitions, obstructions, etc.) Configuration (channel) Water surface profile and Stage Waves (wind, standing, and vessel) Stability (channel) Morphology (aggradation, degradation, meandering, etc.) Structures (bridges, dams, diversions, etc.) Uncertainty (roughness, elevations, transitions, etc.)
Physical	Geology Topography and hydrography Vegetation Sediment (suspended and bed, sizes, physical characteristics, areal distribution, and sources) Uncertainty (surveys)
Environmental	Aesthetics Culture Ecology Archeology
Social	Recreation Access and egress Safety and welfare Displacement

8. Hydraulic Design Presentation. The hydraulic design, as presented in reports, must cover the following:

a. General.

(1) The hydraulic design, as presented in all reports forwarded for either approval or information, should contain sufficient detail to allow an independent assessment as to the soundness of the report conclusions and recommendations. The accuracy and uncertainty of hydraulic design studies (computations, physical, and mathematical modeling) is dependent on the accuracy of input data and the degree to which the computational procedure is representative of the hydraulic phenomena under consideration. For example, water surface profiles determined for a constant cross-section, uniform sloped, concrete channel would be expected to be more accurate and have less uncertainty than those determined for a complex, natural, braided stream.

(2) Uncertainty should be determined following guidance contained in EM 1110-2-1619. The complexity/sophistication of data input and hydraulic design studies is governed by the acceptable risk requirements of the design phase and is to be determined in the project design process. To satisfy the sufficient detail requirement, report contents must be sufficiently descriptive (risk and uncertainty analysis, tables, model calibration, equations, coefficients, model reports, example computations, and a list of data sources).

b. Without-Project and With-Project Conditions. Residual risk for a range of flows, including the consequences of flows exceeding the capacity of project features, will be discussed and shown on the plan and profile sheets. With-project and without-project conditions must be shown on the same sheet for comparative purposes. The design report must include relevant information (e.g., profile and tabular representation) of design flows and computed elevations and define the uncertainty about that information. With-project induced impacts to surrounding areas should be identified and addressed in the project design. To allow for comprehensive evaluation between plans for the full range of flows in reports containing plan comparisons, the same coverage should be provided for alternative plans when the comparison is influenced by conditions exceeding channel capacity.

c. Protective Measures.

(1) Protective measures will be formulated and described by the annual exceedance probability (AEP) with uncertainty, Assurance (also conditional non-exceedance probability [CNP]), and Long-Term Exceedance Probability (LTEP). The design report must indicate the greatest annual exceedance probability event for which the project is formulated in support of the selected plan, including level of assurance. The array of all performance indices should be displayed on a system-wide basis and on individual components that make up the system. Either all elements of the channel must be expected to perform satisfactorily (i.e., should be expected to sustain no more damage than is typically addressed with ordinary maintenance) up to this annual exceedance probability event with the selected level of assurance, or it must be shown that an appropriate allowance has been made for anticipated channel deterioration.

(2) Protective-measure documentation will also include an assessment to demonstrate the extent to which the proposed project can achieve an economical, resilient, and predictable system including risk management of an event exceeding capacity. Project features and alternatives, including resiliency measures should be considered in the formulation to reduce and manage residual life safety risks associated with capacity exceedance (or unacceptable performance) against catastrophic economic and/or life loss scenarios. Economic, environmental, and other benefits derived from these resiliency features will be included in the alternative evaluations. The assessment of such features will consider their contribution to the performance, consequences, residual risk management, and cost of the project.

d. Energy Losses. Energy loss is one factor used in the determination of the amount of risk reduction that can be achieved and protective measures that will help achieve it. These energy loss factors must be as accurately determined as practical; however, due to the inherent uncertainty in determining these loss factors, a range of energy loss values over a range of flows throughout the study reach, including at structures, should be presented. The design report should indicate the procedure used to determine the loss factors; the sensitivity of stage and velocity to the loss factors; and the allowance, as required, for change in these loss factors during the life of the project.

e. Water Surface Profile Stability.

(1) Water surface profile stability is an important element of channel performance considerations and understanding the uncertainty in water surface stability is essential. The design report must indicate the expected stability of the water surface profile throughout the project life (particularly for soft bottom channels) and describe the procedure used in this determination. Channels having low-flow meanders or braids have the least stable profiles and hence greatest uncertainty in anticipating and accounting for changes in bed configuration and bed form. Reporting design measures to provide increased profile stability, such as channel cross-section geometry, grade control structures, protective measures, levees, and floodwalls are subject to the provisions of paragraph 8c.

(2) A sedimentation study is a recommended part of the profile stability design report, and would include such elements as bed load, bed material, bed forms, shoaling and scouring tendencies, bank erosion, etc. Sufficient field data and analysis to define the severity of sediment aspects and substantiate design measures are required. Potential consequences of profile instability, whether preexisting or project-induced, should be identified including impacts to the design profile, lands, structures, and maintenance requirements. Risk analysis procedures as prescribed in EM 1110-2-1619 should be followed.

f. Project geometry. The design report must indicate all sources of floodplain mapping and cross-section geometry utilized in the hydraulic design. Due to the inherent error in any source of geometry, the uncertainty in the cross-section geometry and terrain data utilized in hydraulic modeling, whether cross-sections are derived from traditional survey methods, aerial spot elevations (photogrammetry or light detection and ranging or digital elevation models, must also be presented. The vertical datum for all source data and for the project design should be clearly identified and noted as necessary on profiles and plans.

g. Approach and Exit Channels. The design report must include a discussion of the approach and exit channels. Plan and profile sheets must show these channels which will be considered as part of the project. The extent of these drawings must extend, upstream and downstream, to where the with-project and without-project conditions (paragraph 8b) are essentially the same. Main channel mouths and the lower ends of inflowing tributaries and other entrances and upper ends of distributary channels are to be presented similarly. Where appropriate, the range of tailwater elevation for exit channels (main and distributary) will be presented.

h. Operation and Maintenance. The design report must include an operation and maintenance section that covers hydraulic design aspects. This section will discuss those hydraulic design aspects related to operation and maintenance as required by provisions of 33 CFR 208.10, as approved by the Secretary of the Army. It will form the basis for more detailed information to be included in the Operation and Maintenance Manual furnished to local interests as provided for in the Federal Code. Additionally, if not presented in detail elsewhere, the hydraulic design report will cover matters such as:

(1) Detailed operation and maintenance costs.

(2) Surveillance requirements and permanent features in support thereof, such as benchmarks and staff gages with identified vertical datum.

(3) Real estate needs in support of access, dredging, disposal areas, preclusion of obstructions in flow-way, maintenance of protective measures, and pondage.

(4) Need for closure structures, including the ability of the sponsor to install in a timely fashion.

i. Project Performance. Project performance reporting requirements will be consistent with reference 1(b), and, as a minimum, must address the following:

(1) Annual exceedance probability for each condition/alternative and the long-term risk of capacity exceedance over extended periods of time (e.g., 10-, 30-, and 50-year periods). This must apply to all channels without levees, as well as those with levees and floodwalls.

(2) The percentage of assurance of containing a specific flow event at the target (capacity) stage, given that the specific flow event occurs.

(3) Sources of uncertainty, including water surface profile stability, energy loss factors, cross-section geometry, and model selection and performance.

(4) For mainline and tieback levees and floodwalls, in addition to the above, include and identify design measures to manage capacity exceedance at the least damaging or other planned location. This may include superiority to prevent chain reaction failure of leveed cells, to ensure initial levee overtopping on the least hazardous (damaging) segment, and to prevent an initial breach at pumping stations and other critical locations.

(5) Other design considerations such as trash, ice, debris, and tidal conditions, if not specifically covered above.

j. Care of Water During Construction.

(1) The care of water during construction must be covered for all projects. For projects that could have hazardous-to-life conditions exceeding pre-project conditions during construction, the care of water during construction will be a USACE responsibility with provisions for the care of water during construction designed by the USACE (reviewed and approved by the USACE if the design is accomplished by an architect-engineer contract). When no hazardous condition related to the care of water during construction is foreseen, the construction contract will require the contractor to provide a plan to be approved by the contracting officer.

(2) A construction flood warning plan will be covered for all projects if a need is indicated. For projects extending over several construction seasons, the care of water during construction plans must include contingency measures to ensure the efficacy of constructed portions and to prevent project-incurred damages (upstream of, downstream of, or within the constructed project reach). Permanent measures are to be used if a portion of the project is materially delayed or deleted.

k. Side Drainage. The design report must include all side drainage provisions such as tributaries, sewers, and overland flow. Include the discharge capacity, rationale for its determination, protective measures, and any special provisions if applicable.

Glossary
Typical Local Flood Risk Management Channel Project Features and Terminology

Annual Exceedance Probability (AEP): The probability that a certain threshold may be exceeded at a location in any given year, considering the full range of possible values, and if appropriate, incorporation of project performance. A threshold consists of a metric and a value, and must be specified for each use of AEP. If system performance is considered, then performance should be explicitly accounted for in the description of AEP; similarly, if system performance is not considered then it can be omitted in the description of AEP. Examples of threshold metrics include the stage, flow, surge, and floodplain or flooding extent, and corresponding values may be stated in feet, cfs, depth, etc. Examples of locations include a consequence area index point, a specific grid cell, or a fragility curve location (also referred to as system response probabilities). An example statement of AEP without performance is: "The boundary of the Federal Emergency Management Agency (FEMA) 100-year floodplain has a 1 percent AEP, and the entire FEMA 100-year floodplain corresponds to the aerial flooding extent where flood depths are greater than 0 feet." An example of AEP with performance is: "The resultant AEP with a depth greater than 0 feet at location XX is 1% while taking into account levee performance."

Assurance: The probability that a target stage will not be exceeded during the occurrence of a flood of specified exceedance probability considering the full range of uncertainties. Term selected to replace "conditional non-exceedance probability" (CNP).

Approach Channel: That portion of the flow-way upstream of the constructed project that encompasses an altered regime.

Bed and Bank Protective Measures: Riprap, gabions, groins, concrete, concrete blocks, and vegetation used to protect the channel bed and/or banks from erosion.

Channel: The portion of the project carrying flow. Descriptive adjectives are used to denote specific types such as natural, constructed, riprapped, concrete, trapezoidal, leveed, overbank, low flow, and bypass.

Channel Stabilization: Pile dikes, groins, etc., as well as grade control structures and bed and bank protective measures.

Conditional Non-Exceedance Probability (CNP): see Assurance.

Economic Risk: "Economic risk" is the combination of likelihood and harm to property, infrastructure, and other assets as well as economic systems all measured in monetary terms. A common metric of economic risk is expected annual damage (EAD). EAD is the result of integrating the damage-probability functions.

Exit Channel: That portion of the flow-way downstream of the constructed project that encompasses an altered regime.

Grade Control Structures: Sills, weirs, and drop structures that traverse the channel to stabilize the invert slope and/or control the velocity.

Hazard (Flood): An event or physical condition that has the potential to cause fatalities, injuries, property damage, infrastructure damage, agricultural loss, damage to the environment, interruption of business, and other types of loss or harm. The degree of flood hazard varies with circumstances across the full range of floods.

Levees and Floodwalls: A manmade barrier (embankment, floodwall, or structure) along a water course or water body constructed for the primary purpose of excluding flood waters from the leveed area, that have arisen from hurricanes, storms, seasonal high water, storm or earthquake surges, precipitation, and other weather events.

Long-Term Exceedance Probability (LTEP): The probability of capacity exceedance during a specified period. For example, 30-year exceedance probability refers to the probability of one or more exceedances of the capacity of a measure during a 30-year period; formerly long-term risk. This accounts for the repeated annual exposure to flood risk over time.

Project Performance: The system's reaction to the hazard. Performance refers to the system features and the capability to accommodate the flood hazard as a single event or load. In this manual, this would be termed "system performance" (also termed "engineering performance"). Performance also refers to the metric that describes the capability of the system to accommodate a single event (Assurance [also CNP]) and the full range of events (AEP and LTEP). In that light, in addition to the levee failure probability functions, performance can also be described by the interior-exterior functions for leveed areas; unregulated-regulated transforms for reservoirs and diversions; and elevation-discharge functions (rating curves) for channels. These too would be considered "system performance." When the structural integrity of a system or system component is discussed, such as the fragility function, the reference would be termed "structural performance." When the economics of a system is discussed, the reference would be termed "economic performance." The performance of an item is described by various elements, such as flood risk management, reliability, capability, efficiency, and maintainability. Design and operation affect system performance.

Protective Measures: See Bed and Bank Protective Measures.

Reliability: The likelihood of successful performance of a given project element over a specified period of time.

Residual Risk: The flood risk that remains in the floodplain after a proposed flood risk management project is implemented. Residual risk includes the consequence of capacity exceedance and consideration of project performance.

Resilience: The ability to anticipate, prepare for, and adapt to changing conditions and withstand, respond to, and recover rapidly from disruptions (source: Executive Order 13653, Preparing the U.S. for the Impacts of Climate Change).

Risk: The likelihood and severity of adverse outcomes; for this ER, the focus is on the risk from flooding. Risk is often measured as potential or mean loss-of-life, property damage, and/or ecosystem losses and may also include uncertainty over the benefits to be gained from a proposed or actual action taken. Usually, both the likelihood and the consequence are to some degree uncertain.

Risk Assessment: A systematic approach for describing the nature of the risk, including the likelihood and severity of consequences. Risk assessments can be qualitative, semi-quantitative, or quantitative. Risk assessment includes explicit acknowledgment of the uncertainties in the flood risk.

Risk Management: A decision-making process in which risk reduction actions are identified, evaluated, implemented, and monitored. The purpose of risk management is to take actions to effectively reduce and manage risks identified in the risk assessment.

Risk Communication: A two-way exchange of information between risk assessors and those who will use the risk assessment results or those who are affected by the risks and risk management actions. Open communication improves the understanding of the risks by all parties, and leads to improved risk assessments and risk management decisions and outcomes.

Side Drainage: Such structures as culverts, outfalls, chutes, and channels with appropriate energy dissipators used to control the entry of adjacent drainage.

Special Features: Pump stations, ponding areas, junctions, bridge abutments and piers, diversion dams, transitions, and recreational and social provisions.

Uncertainty: Uncertainty is the result of imperfect knowledge concerning the present or future state of a system, event, situation, or (sub) population under consideration. Uncertainty leads to lack of confidence in predictions, inferences, or conclusions. It is important to distinguish uncertainty that results from a lack of knowledge from the uncertainty that results from natural variability.

> **Knowledge Uncertainty**: Lack of knowledge regarding the true value of a quantity. Uncertainty is a consequence of reliance on limited data and on conceptual and mathematical models. This category of uncertainty is formally labeled epistemic uncertainty. Uncertainty is a measure of imprecision of knowledge of parameters and functions used to describe the hydraulic, hydrologic, geotechnical, and economic aspects of a project plan.
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> **Natural Variability**: The distribution or spread of values within a natural "population" or data set. This array of possible values in a population is caused by the inherent randomness of natural or social systems, and is formally labeled aleatory uncertainty. The values in the statistical population have some probability distribution, and only limited knowledge of the entire statistical population and the probability distribution may exist. Sometimes variability is classed as a type of uncertainty, although generally it

should not be confused or interchanged with uncertainty as defined above. Variability is the notion that there is a range of possible values that will occur and not the lack of knowledge about that range or the distribution of those values.